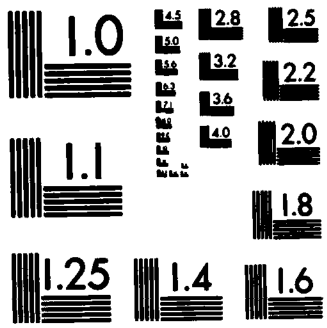
AD-A144 208   PARAMETER MEASUREMENT METHODS FOR INTERFACING HYDRAULIC   1/2
SYSTEMS WITH MICR..(U) OKLAHOMA STATE UNIV STILLWATER
FLUID POWER RESEARCH CENTER E C FITCH ET AL. NOV 83
UNCLASSIFIED OSU-FPRC-83-A-S1 DAAK70-82-C-0162   F/G 13/7   NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Report No. FPRC 83-A-S1

PARAMETER MEASUREMENT METHODS FOR INTERFACING HYDRAULIC SYSTEMS WITH MICROELECTRONIC INSTRUMENTS AND CONTROLLERS

PREPARED FOR

U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA 22060

PREPARED BY

PERSONNEL OF THE
FLUID POWER RESEARCH CENTER
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLAHOMA

CONTRACT NUMBER
DAAK70-82-C-0162

10

Report No. FPRC 83-A-5.

PARAMETER MEASUREMENT METHODS FOR INTERFACING HYDRAULIC SYSTEMS WITH MICROELECTRONIC INSTRUMENTS AND CONTROLLERS

PREPARED FOR

U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA 22060

PREPARED BY

PERSONNEL OF THE
FLUID POWER RESEARCH CENTER
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLAHOMA

CONTRACT NUMBER
DAAK70-82-C-0162

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: OSU- FPRC 83–A–S1	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Parameter Measurement Methods for Interfacing Hydraulic Systems with Microelectronic Instruments and Controllers	5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report 25 Sept. 1982–24 Sept. 1983
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Fitch, E. C.; Hong, I. T.; Mortensen, J.	8. CONTRACT OR GRANT NUMBER(s): DAAK70-82-C-0162
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Fluid Power Research Center, Oklahoma State University, Stillwater, OK 74078	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Mobility Equipment Research & Development Command Procurement & Production Office, Ft. Belvoir, VA 22060	12. REPORT DATE: November, 1983
	13. NUMBER OF PAGES: 136
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): ONRRP, Rm. 582, Federal Bldg., 300 E. 8th Street, Austin, TX 78701	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Parameter Measurement	Computer Interface	Microcomputer Contro[illegible]
Hydraulic Systems	Sensor Specification Sheet	Distributed Intelligence
Sensors	Sensor Selection	
Sendor	Condition Monitoring	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of effort carried out in the gathering, organization [illegible] compilation of technical data available on parameter measurement devices for hydraulic [illegible] tems. Based on the compilation of data, specification formats were developed for assis[illegible] in the selection and procurement of parameter measurement system components.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SUMMARY

This report presents the results of work done under U.S. Army MERADCOM Contract No. DAAK70-82-C-0162. The purpose of this research is to solicit, organize, and compile technical data on parameter measurement systems that are suitable for fluid power applications. Based on the compilation of data, specification formats will be developed for assisting in the procurement and selection of parameter measurement system components. The objectives of this research have been met successfully.

PREFACE

This report was prepared by the Staff of the Fluid Power Research Center (FPRC), Oklahoma State University, under the direction of Dr. E. C. Fitch. The work reported here was authorized by U.S. Army MERADCOM Contract No. DAAK70-82-C-0162. The report documents the work completed under the subject contract covering the period 25 September 1982 to 24 September 1983.

The principal investigator for this effort was Dr. E. C. Fitch. Project personnel were:

I. T. Hong

J. Mortensen

E. J. Lee

G. Silva

T. Ito

The contract officer technical representative for this contract was Mr. Delmar Craft.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

CHAPTER I

INTRODUCTION

Faced with the prospect of assuring the development of accurate and reliable hydraulic systems, designers and users depend more on system monitoring and control. Condition monitoring offers a means of detecting and assessing incipient and impending failures of hydraulic systems. The monitored data provide information either for fault detection or operation control, or both of them. As a result, the incorporation of electrohydraulic control will tend to complement onboard monitoring and create totally new design options.

It is generally accepted that the microcomputer is destined to serve as the data processing and control bases for new hydraulic systems. As this occurs, many traditional designs involving mechanical, hydraulic and pneumatic concepts will become obsolete and will eventually be replaced. The trend which exists will be paced by the availability and effective use of parameter measurement devices rather than by the continual progress of microcomputer developments. As far as hydraulic systems are concerned, microcomputers are worthless without an effective means of interfacing them with the external system itself.

Parameter measurement methods play an important role since they must not only translate a physical effect, in their own environment from the analog world into electrical signals or readouts, which are meaningful in the "outside" world; but also, in the future, these electrical signals must be transmitted to and interfaced with digitally-organized central processors. That is, in the analog world, parameters are normally continuous, but microsystems engineers require discrete event or digital type signals.

In any parameter measurement system, there are three major elements -- detector, signal modifier, and process unit. The function of the detector is to respond (be sensitive) to the magnitude (or changes in the magnitude) of physical or chemical quantities and transmit an output signal proportional to the magnitude of the parameter with acceptable fidelity. A detector (or sensor) is considered to be an element employed by an instrument transducer to sense the desired quantity. It should be noted that a transducer may not be a sensor. The distinction must be made between input transducers (sensors), which convert a non-electrical quantity into an electrical signal, and output transducers (sendors), which convert an electrical signal into a non-electrical quantity.

The signal modifier of a parameter measurement system receives the output signal of the detecting element (sensor) and modifies it by amplification or suitable shaping of its waveform, so that the signal is appropriate for display or further processing; for instance, signal amplifiers and filters.

The signal processing unit may be anything from a simple display light or meter to a full-blown, microcomputer-based diagnostic monitor or operational controller. The term "monitor" is reserved for an information processor that receives an electrical signal, checks and perhaps converts it according to a specified algorithm, and finally produces or transmits an output to regulate the parameter, control some part or all of the operation, and/or display or reflect the status of the hydraulic system.

Transducer candidates for many useful fluid power system parameters have been emerging, based upon a bewildering variety of technical concepts. Although the field remains in developmental ferment, the need for identifying appropriate instrument transducers is so great that it would be technically disastrous to wait until a steady-state condition was reached. The old image of the transducer as a "gadget" is gone, but the struggle for priority with respect to effort and funds for transducers continues to restrict their development and growth.

Transducers today have tended to be available only in small quantities and at high unit cost. This was generally acceptable in the past because they were used in conjunction with even costlier analog electronics or on limited production systems, where price was not a restrictive factor. The availability of low-cost microelectronics signal processors (monitors and controllers) is giving a new incentive to the development of low cost and a greater variety of instrument transducers than existed in the past. With this surge of activity producing new transducers, together with those already on the market, it stimulates the need to:

* identify what transducers are available today,
* describe commercially available transducers in such a way that will facilitate selection, and
* formalize effective specification criteria for transducers that will help foster further development and applications.

This report presents the results of efforts carried out in the gathering, organization, and compilation of technical data available on parameter measurement devices for hydraulic systems. Based on the compilation of data, specification formats were developed for assisting in the selection and procurement of parameter measurement system components. The specification sheets for most commonly used transducers are presented in Chapter III.

CHAPTER II

FUNDAMENTALS OF PARAMETER MEASUREMENT DEVICES

GENERAL CONSIDERATIONS

The function of a parameter measurement system is accomplished by converting the nonelectrical quantity to be measured into an electrical form; thus, a pickup, sensor or detector is needed. In this chapter, the classification measuring principles and generalized performance characteristics of sensors are discussed. Furthermore, the characteristics of signal modifiers and processors are presented. In this aspect, major emphasis is placed on the conceptual approach to computer interfacing requirements.

The description of a sensor can be confusing because they are identified in at least five different ways in the technical literature:

* Measurand -- the basic and derived quantities
* Transduction Principle
* Passivity
* Construction Features
* Effective Range

The measurand is the physical quantity, property or condition which is sensed or measured. Thus, the measurand represents a universally understandable aspect which offers the most useful means of identifying and classifying sensors for hydraulic system applications. The measurand quantity or variable may, for example, be the displacement; whereas, the basic variable type might be linear or angular. Table 2.1 shows derived quantity and basic measurand.

The transduction principle of a sensor is the physical effect or effects employed to translate the quantity of the measurand into an electrical signal. The energy inputs accepted by electrical sensors are the following: mechanical, thermal, mass, chemical, and electromagnetic. In general, these energy inputs are converted into an electric signal using two parameters -- mechanical displacement and velocity. The importance of the mechanical sensing element of a sensor is therefore obvious. A spring, for example, converts a force or torque into a displacement; a diaphragm converts pressure into a displacement.

The passivity of a sensor is concerned with its signal energy characteristics. If a sensor is passive, it derives energy from the measurand and is self generating in terms of initial signal power. An active sensor must be excited externally. Such a sensor receives its power from an external source and merely modulates the signal in proportion to the magnitude of the measurand.

The construction features of a sensor provide an adequate basis upon which to describe and identify a sensor. The detection mechanism offers one construction feature; namely, the mechanical sensing element, such as a diaphragm or bourdon tube. Another important construction feature is that of fabrication and uniqueness. A list of some of the more popular construction features of sensors is given in Table 2.2.

Table 2.1. Illustration of Derived Quantity and Basic Measurand.

DERIVED QUANTITY	BASIC MEASURAND
LENGTH WIDTH THICKNESS POSITION LEVEL EROSION WEAR SURFACE QUALITY STRAIN VIBRATION	LINEAR DISPLACEMENT
ATTITUDE ANGLE OF TURN ANGLE OF INCIDENCE ANGLE OF FLOW ANGULAR VIBRATION	ANGULAR DISPLACEMENT
SPEED RATE OF FLOW MOMENTUM VIBRATION	LINEAR VELOCITY
ANGULAR SPEED RATE OF TURN (roll, pitch, yaw) ANGULAR MOMENTUM ANGULAR VIBRATION	ANGULAR VELOCITY
VIBRATION FORCE IMPACT (jerk) MASS STRESS	LINEAR ACCELERATION
ANGULAR VIBRATION TORQUE ANGULAR IMPACT MOMENT OF INERTIA	ANGULAR ACCELERATION
WEIGHT THRUST DENSITY STRESS TORQUE PRESSURE ALTITUDE FLUID VELOCITY SOUND ACCELERATION	FORCE
HEAT FLOW FLUID FLOW GAS PRESSURE GAS VELOCITY ANGLE OF FLOW TURBULENCE SOUND	TEMPERATURE
LIGHT FLUX & DENSITY SPECTRAL DISTRIBUTION LENGTH STRAIN FORCE TORQUE FREQUENCY NUMBER	LIGHT
FREQUENCY NUMBER STATISTICAL DIS- TRIBUTION	TIME

Table 2.2. The Construction Features of Sensors.

CONSTRUCTION FEATURES	
DETECTION	**UNIQUENESS**
DIAPHRAGM	BONDED
TURBINE	UNBONDED
FLOAT	THIN FILM
SEMICONDUCTOR	DIFFUSED
PLATINUM WIRE	BONDED BAR
HOT WIRE	ENCLOSED
GYRO	OIL—DAMPED
BELLOWS	SELF—GENERATING
BOURDON—TUBE	SERVO
CAPSULE	VIBRATING WIRE
LVDT	AMPLIFYING
HALL EFFECT	DC OUTPUT
ULTRASONIC	DIGITAL OUTPUT
FORCE BALANCE	FREQUENCY OUTPUT
	INTEGRATING

The final descriptive factor or means of identifying sensors is the effective range over which the measurand can be sensed. Of course, the range values must be accompanied by the associated units of the measurand -- for example, a pressure sensor is typically identified as a 0 to 5,000 psi sensor.

OPERATING PRINCIPLES

As illustrated in Chapter I, a parameter measurement system essentially consists of three major elements -- sensor, signal modifier, and process unit. This section presents the basic operating principles of these elements, which provide instrument users with conceptual information from which to select devices adequately.

Sensors

A sensor has been defined as a device which converts the magnitude of the applied stimulus from a measurand into an electrical signal proportional to the quantity of the stimulus; thus, the operating principle of a sensor is the physical effect or effects employed to convert the quantity of the measurand into a sensible signal. The subject of this study is concerned with the investigation of parameter measurement methods for interfacing a hydraulic system with microelectronic instruments and controllers; therefore, the operating principles of sensors discussed and illustrated in this section are restricted to electrical effects -- those which convert an energy input into an electrical signal. In general, electrical sensors accept the energy inputs from mechanical, thermal, mass, photo, and electromagnetic effects. These physical effects can be transduced into electric signals by means of energy-conversion principles (for example, a thermocouple converts thermal energy into electric energy) and energy-controlling principles (for example, a resistive transducer converts the geometrical change of a physical object into a change of resistance). Although there are various sensors available for different applications, the operating principle of sensors is governed by some basic electrical properties (which may be capacitance, resistance, inductance, or a combination of these). The following paragraphs summarize the fundamental operating principles of sensors. Detailed descriptions of sensing methods for the most commonly used sensors are illustrated in Chapter III.

Capacitance Effect -- Operates by varying the gap between plates, changing the area of plates or by changing the dielectric constant of the dielectric. The design shown in Fig. 2.1 depends on the displacement of the movable teeth to change the area in common to both sets of teeth. This varying area causes the capacitance to change in relation to the displacement. In Fig. 2.2, the air is used as the dielectric of the capacitance. By changing the displacement of the movable plate, the amount of dielectric changes, thus resulting in a change in the capacitance.

Inductance Effect -- The reluctance of a magnetic circuit can be changed by varying the length of the flux path, its cross-sectional area, or its permeability -- these changes all cause the inductance of the coil to change. In Fig. 2.3, an applied load changes the

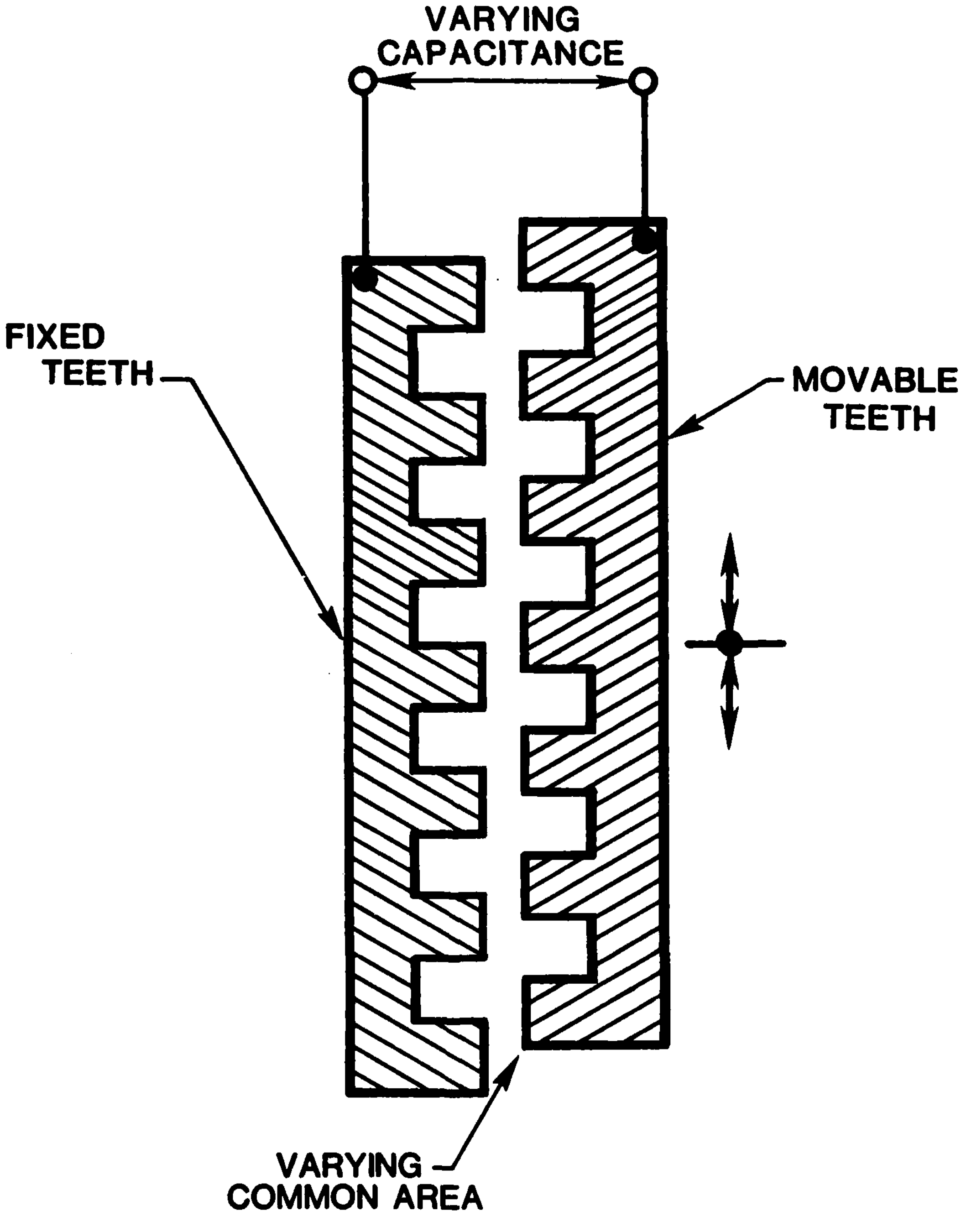


Figure 2.1. Capacitance Effect Sensor, Type I.

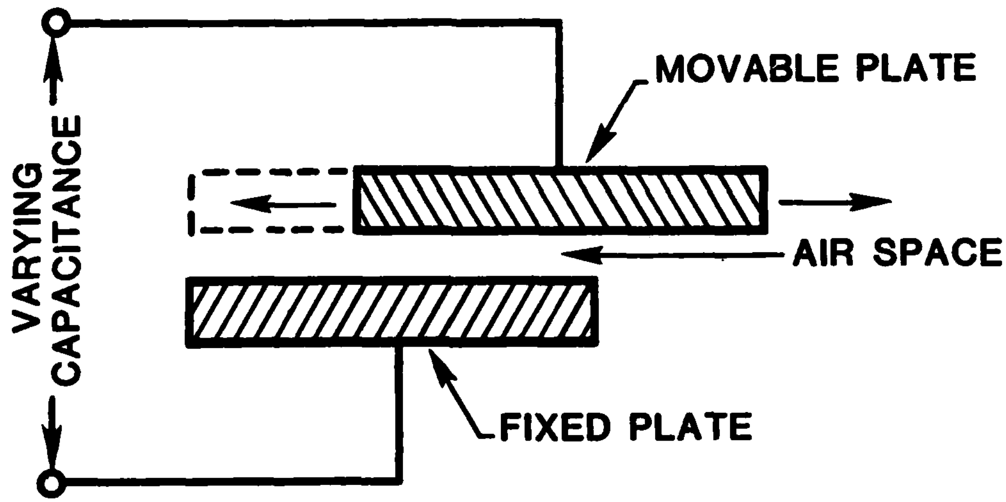


Figure 2.2. Capacitance Effect Sensor, Type II.

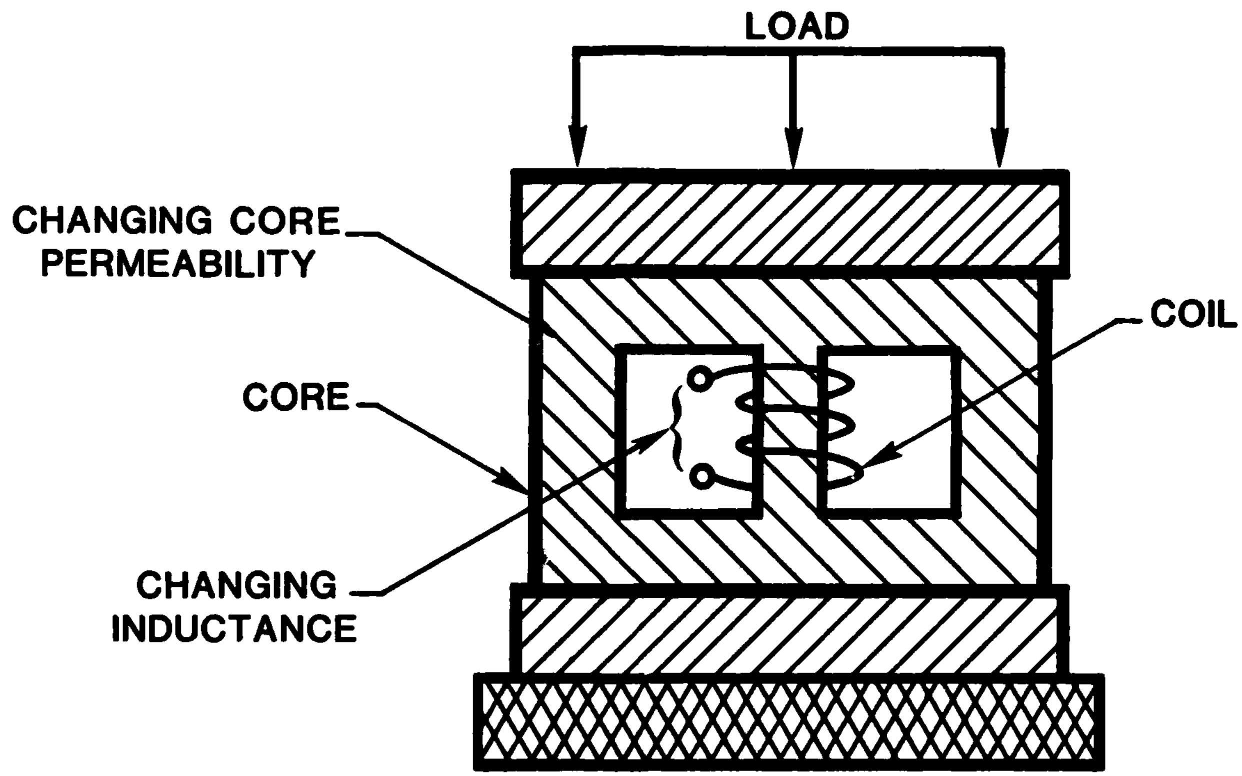


Figure 2.3. Inductance Effect Sensor.

permeability of the core material, which results in a change in the inductance of the coil.

Resistance Effect -- The resistance of a conductor varies with the coefficient of resistance of the material, the physical length, and with the cross-sectional area. Any method of varying one of these parameters can be the basis for a resistance type sensor. In Fig. 2.4, an applied force causes the conductor to elongate and the diameter to decrease. These dimensional changes cause the resistance of the conductor to increase. In Fig. 2.5, the position of the movable wiper determines the amount of the resistive conductor that is between the wiper and the end. The amount of resistance is proportional to this amount of conductor.

Thermal Effect -- Many devices are designed to convert the heat energy into electrical or magnetic energy such that the temperature of an object can be monitored. In Fig. 2.6, the applied heat energy causes the resistivity to change. A change in resistance is directly proportional to the change in heat energy, which is a function of the temperature.

There are also a lot of theories postulated to monitor heat energy; for example, the Ettingshausen effect, Nernst effect, Righi-Leduc effect, Seebeck effect, Pettier effect, and Thomson effect. These theories explain the heat-electrical energy conversion method differently. However, they all follow the same basic principle -- the change in thermal condition induces the change in electrical condition.

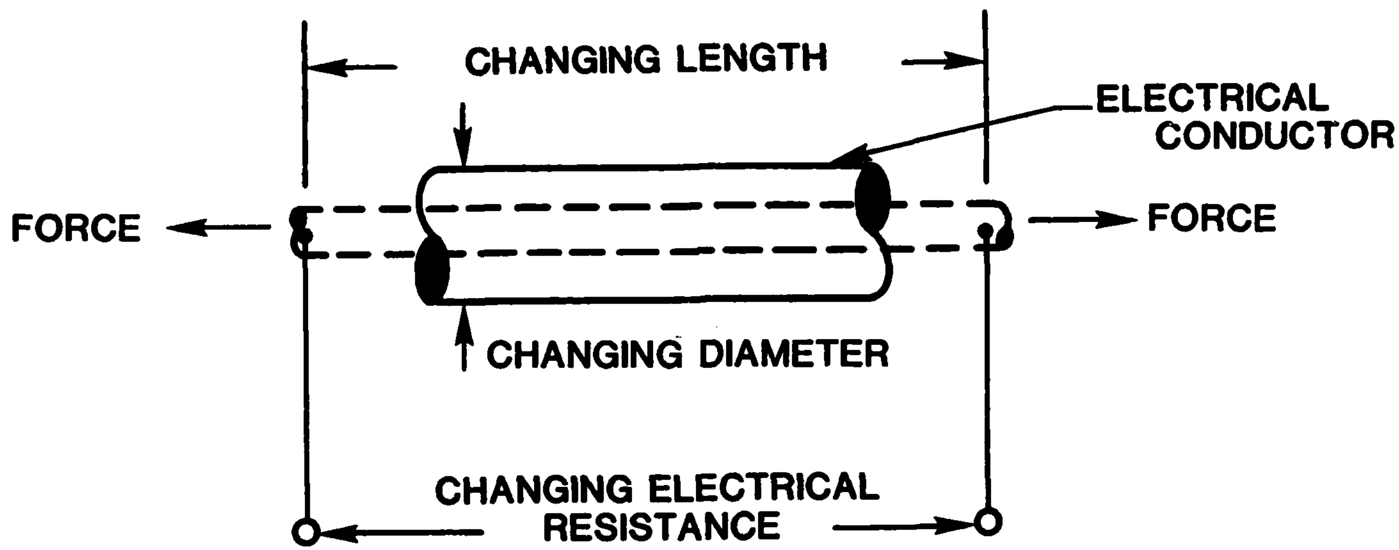


Figure 2.4. Resistance Effect Sensor, Type I.

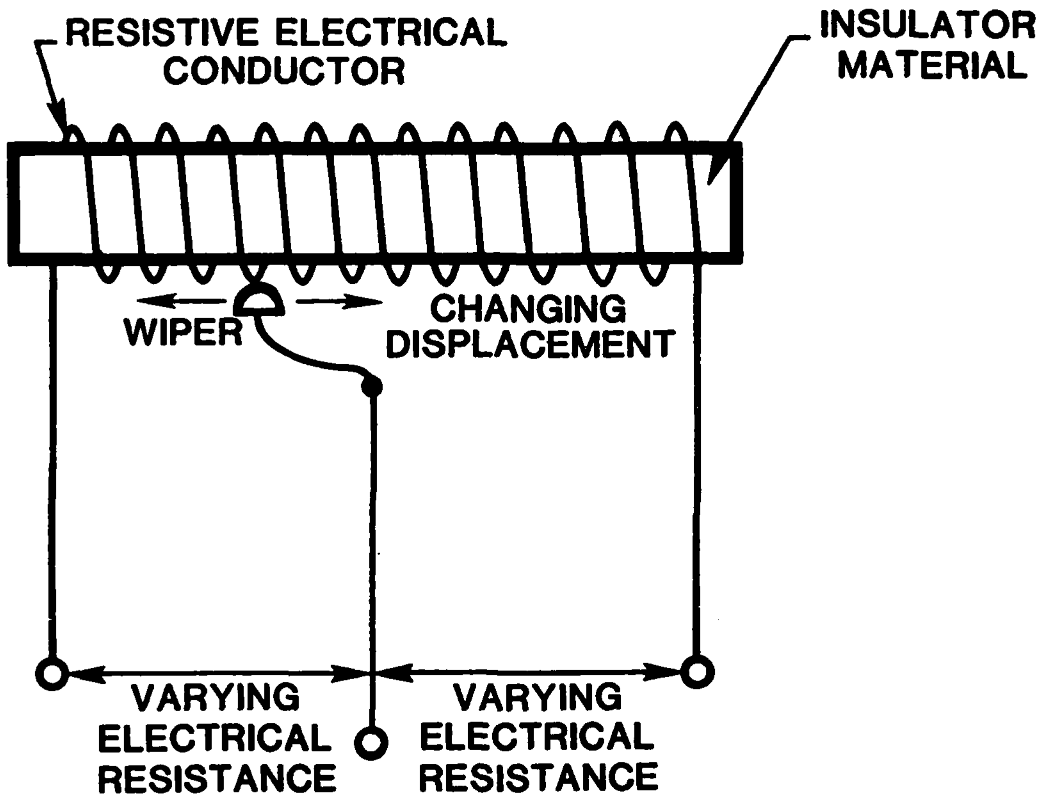


Figure 2.5. Resistance Effect Sensor, Type II.

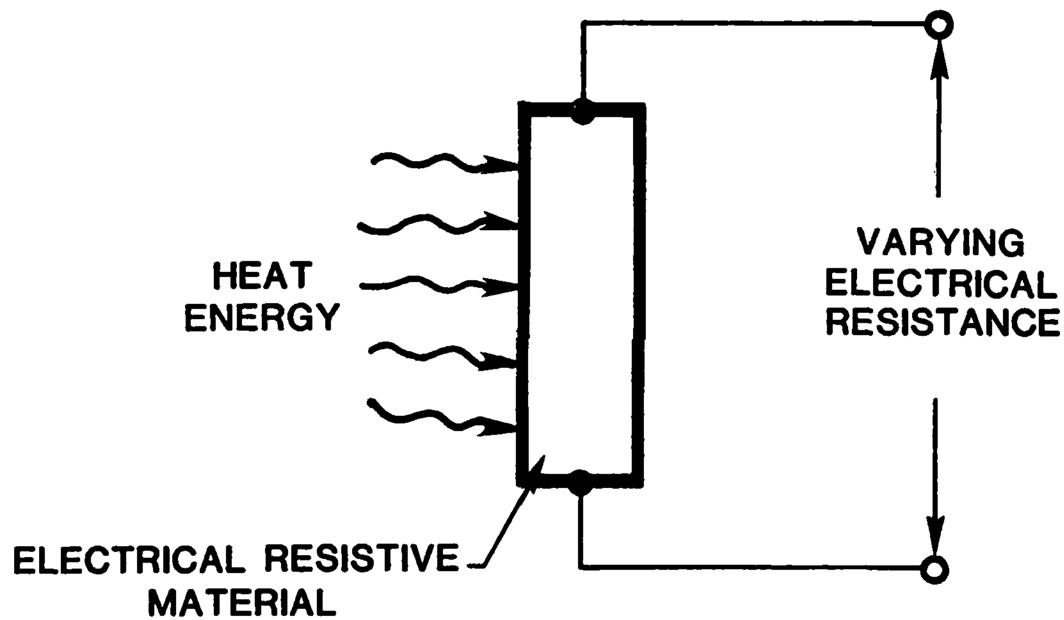


Figure 2.6. Thermal Effect Sensor.

Piezoelectric Effect -- This is the production of a potential across opposite faces of a material as a result of crystal lattice deformation. The compression of a crystal of quartz or Rochelle Salt generates an electrostatic voltage across the crystal; and, conversely, application of an electric field may cause the crystal to expand or contract. Sensors using this principle are normally for dynamic measurements, are self-generating, rugged, and can have high outputs. In Fig. 2.7, hydraulic pressure exerted on the material causes it to deflect, resulting in a charge being developed between the two electrodes.

Photo Effect -- This effect is caused by the variation of illumination, which results in a change in the electrical energy level. Generally, it is distinguished by three major types: photoconductive, photoelectric, and photovoltaic effects.

In the photoconductive case, electromagnetic radiation -- normally light -- will change the conductivity of certain substances (such as selenium, germanium, etc.). This effect is illustrated in Fig. 2.8, where a change in the intensity of the light energy causes a change in the electrical resistance of the semiconductor material.

The photoelectric effect is the liberation of electrons from a surface subjected to light. As illustrated in Fig. 2.9, light energy falling on the emitter material causes the electrons in the material to gain enough energy to be emitted. The voltage source causes a positive potential to be felt on the collector, thus causing the electrons

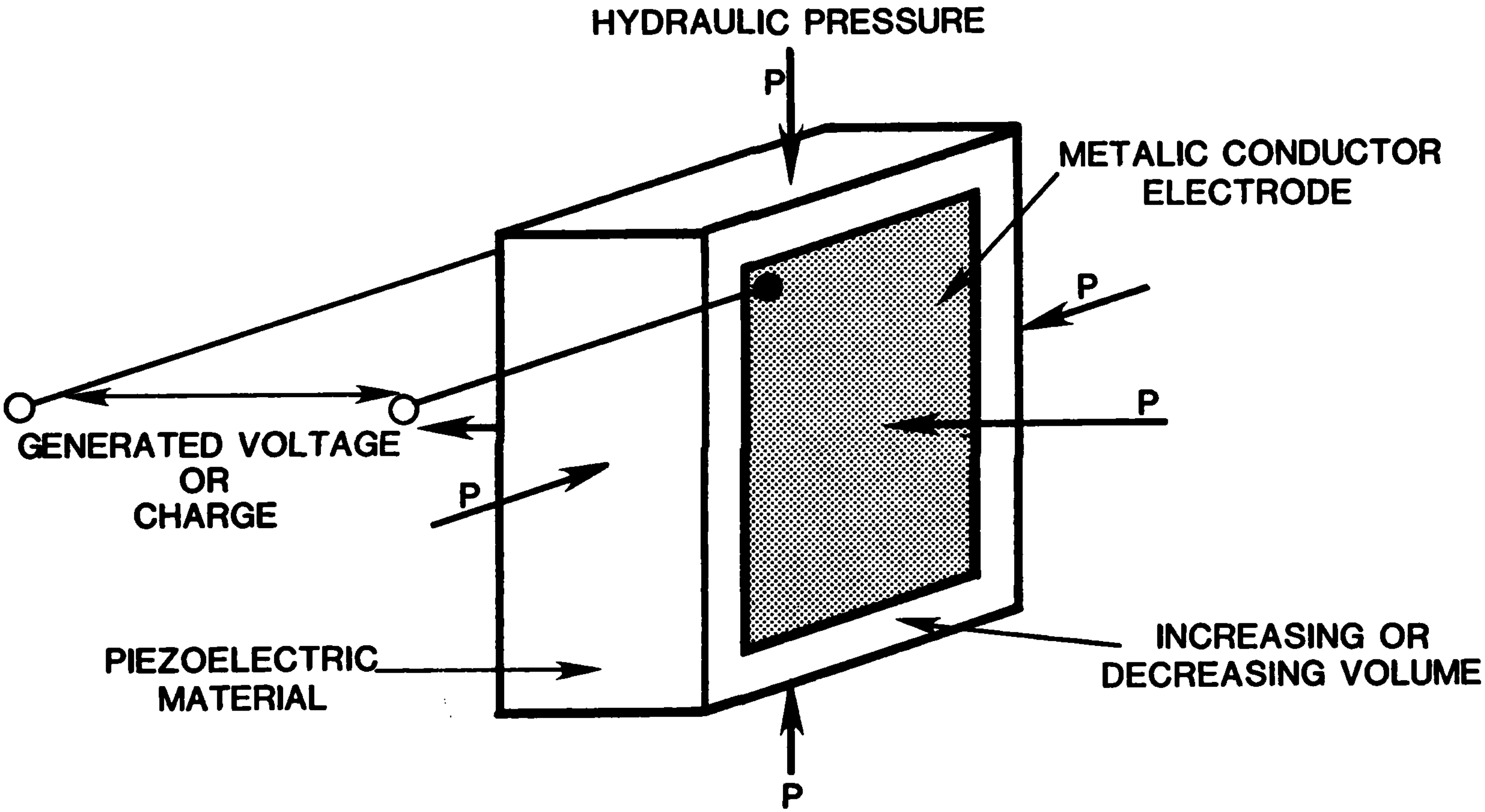
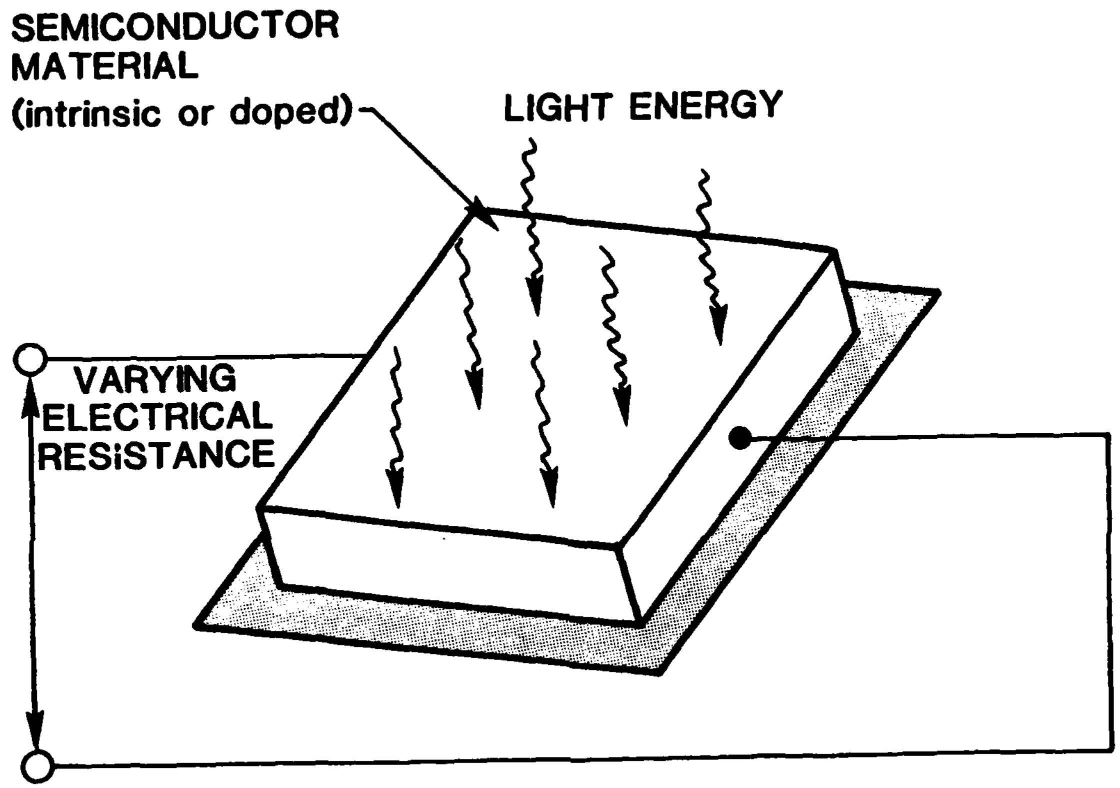


Figure 2.7. Piezoelectric Effect Sensor.



PHOTOCONDUCTIVE

Figure 2.8. Photoconductive Sensor.

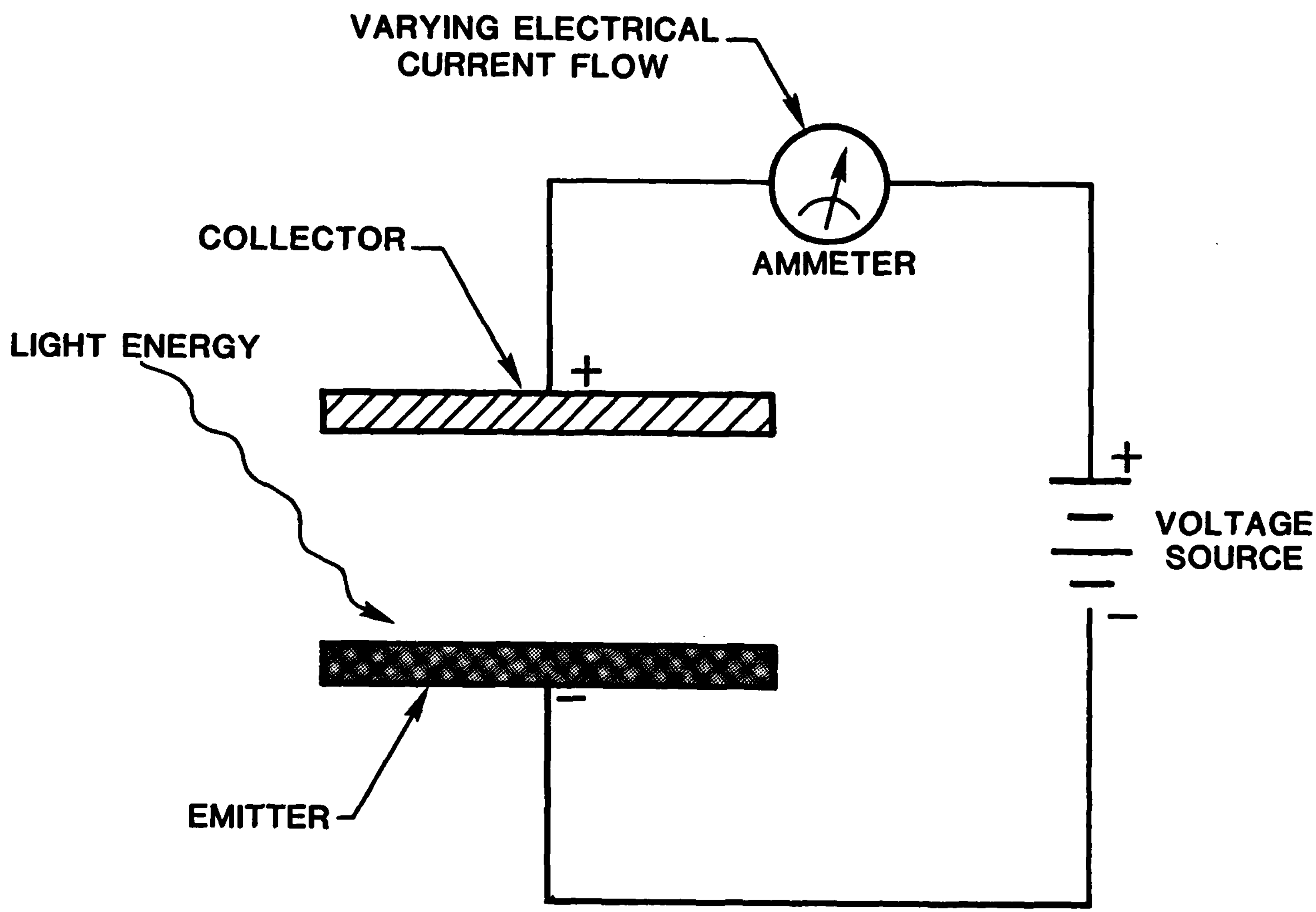


Figure 2.9. Photoelectric Sensor.

emitted from the emitter to be drawn to the collector.

The solar cell is the typical example of the photovoltaic effect in which an electromotive force (emf) is produced by radiant energy, usually light, incident upon the junction of two dissimilar materials. These devices are self-generating and produce a voltage proportional to light density. In Fig. 2.10, the incident light energy falling upon the P-N junction causes a voltage to be developed between the transparent electrode and the base material.

The transduction principles summarized in the above paragraphs are useful for sensor considerations. Although not exhaustive, the principle given can provide the basis for selection rationale and judgment.

Signal Modifiers and Signal Processors

Sensors generally require some type of circuitry or equipment in order to function and display the magnitude of the measurand. All passive type sensors and many active sensors require supporting electronics. This signal conditioning equipment, or signal modifier, supplies the sensor's operating power, amplifies its output signal when required, and provides the zero reference in analog-output sensors. Some sensors may require that additional functions be performed (such as analog-to-digital (A/D) conversion, filtering, or other signal processing). The complexity of the signal-conditioning electronics varies from one type sensor to another because many sensors have supporting circuitry built in.

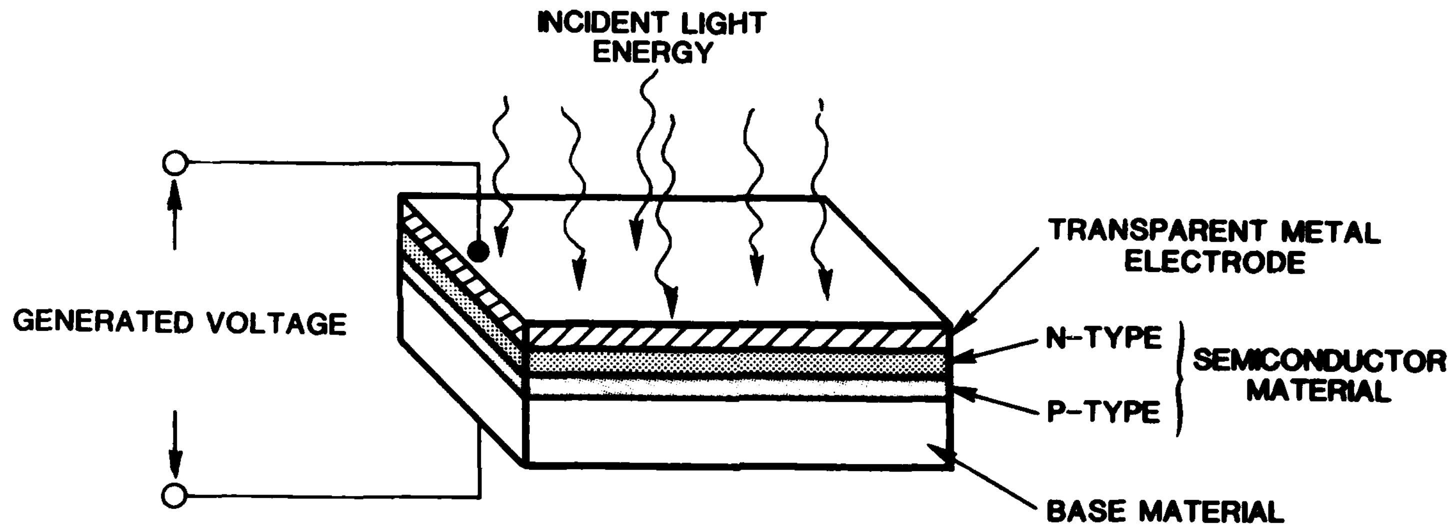


Figure 2.10. Photovoltaic Sensor.

Knowledge of signal conditioning for interfacing sensors with the real world is vital to tneir selection and application. Since sensors are the sensory elements needed for microcomputer control and condition monitoring of modern machines, sensor interfacing cannot be overlooked. The following sections give insight into the operating principles of how to approach signal conditioning and interfacing problems.

Computer Interfacing Circuit

To interface an analog sensor to a computer or a digital circuit, the sensor's analog signal must be converted to a digital code. This conversion is usually implemented with an analog-to-digital converter (ADC). There are many different types of ADC's available, and each is chosen over the other types due to the specifications of the particular application. Rarely can an analog signal be fed directly into an ADC because the ADC has a requirement on the input signal that has to be met, usually a voltage signal varying from 0 to 5 or 0 to 10 volts D.C. Most sensors are active devices requiring an external power source to excite them and provide a varying electrical signal. The output electrical signal from a sensor must be scaled so that its signal will have the same range as the input requirements of the ADC. This scaling is accomplished through the use of an instrument amplifier. A filter may also be required to eliminate any noise in the analog signal that may cause an error.

Figure 2.11 illustrates a typical sensor (transducer) computer interface. The physical parameter is converted to an electrical

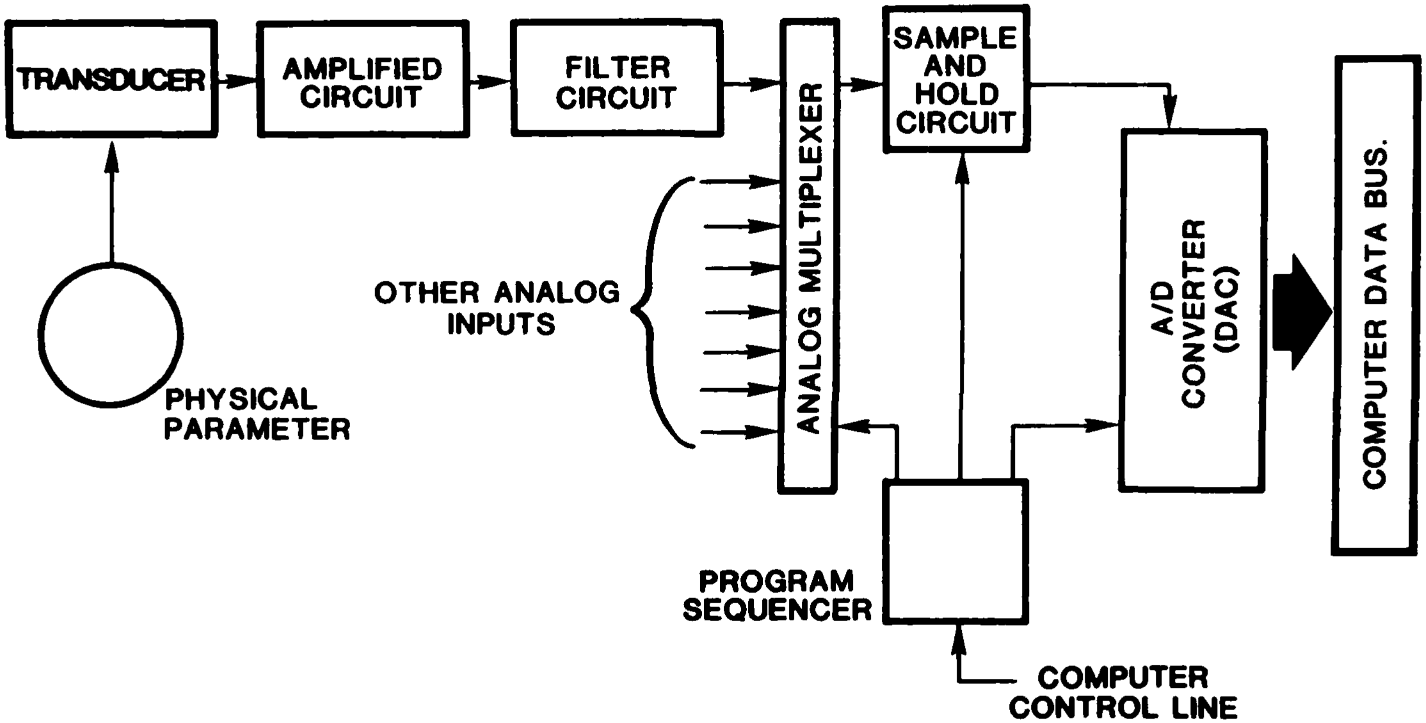


Figure 2.11. Typical Transducer/Computer Interface.

parameter or signal, which is then scaled to the proper range in the amplifier circuit. The signal is then filtered to remove any noise. An analog multiplexer is used so that many analog channels may be used; this is not a necessary stage. A sample and hold circuit then takes a snapshot of the signal and saves the value for the ADC. Finally, the ADC converts the analog signal to an appropriate digital representation. The computer controls the entire operation by the use of control lines into the program sequencer. The program sequencer selects which analog channel to sample and tells the sample-and-hold circuit to take its sample and, finally, tells the ADC to start its conversion. After the conversion is complete, the digital code is available to the computer. The whole sequence can then be repeated. This description illustrates a typical sensor-to-computer interface. There are other interface configurations that have advantages in particular situations, but Fig. 2.11 shows what is generally needed. The operating principle of each individual component in Fig. 2.11 will be covered in the following sections.

Amplifier Circuits

As was stated earlier, vary few sensors have an output signal of the correct type and range for the ADC. For example, a Type J thermocouple produces an output voltage ranging from 0.000 to 27.388 millivolts for temperatures ranging from 0°C to 500°C. This is a change of less than 55 microvolts per degree of temperature change. By using an instrument amplifier and adjusting the gain and offset, the signal can be changed to range between 0 and 10 volts for the temperature range of 0°C to 500°C.

In the past, an instrument amplifier capable of high accuracy and resolution was quite expensive. Therefore, configurations such as Fig. 2.12 had to be used to utilize an instrument amplifier and ADC for many analog input channels. The cost of the amplifiers came down as solid-state electronics advanced, allowing higher quality and less expensive amplifiers to be configured, as in Fig. 2.13, so that each analog input has an instrument amplifier associated with it.

An amplifier must perform one or more of the following functions: boost the signal amplitude, convert the sensor signal to a voltage, provide a buffer for the signal, or extract the differential signal and reject the common mode signal. To implement these functions requires a variety of amplifier types.

The most popular type of amplifier is the operational amplifier, which can be configured in many different closed-loop connections to implement the required amplifier stage function. Figure 2.14 shows some of the most common and useful op-amp configurations. The op-amp is a good amplifier choice in general where a single-ended signal is to be buffered, amplified, or converted from current to voltage. Op-amps may also be used in filtering circuits; these will be covered later.

Since most sensor signals will be differential in nature, one varying and one fixed reference signal, an op-amp with a single-ended input

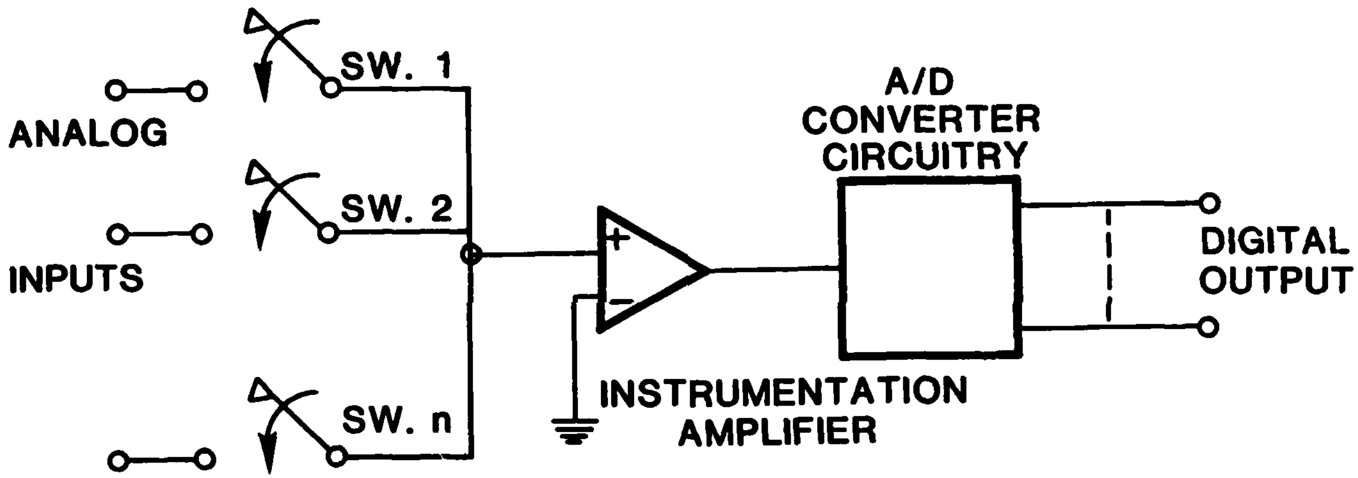


Figure 2.12. Conventional Instrument Amplifier Configuration.

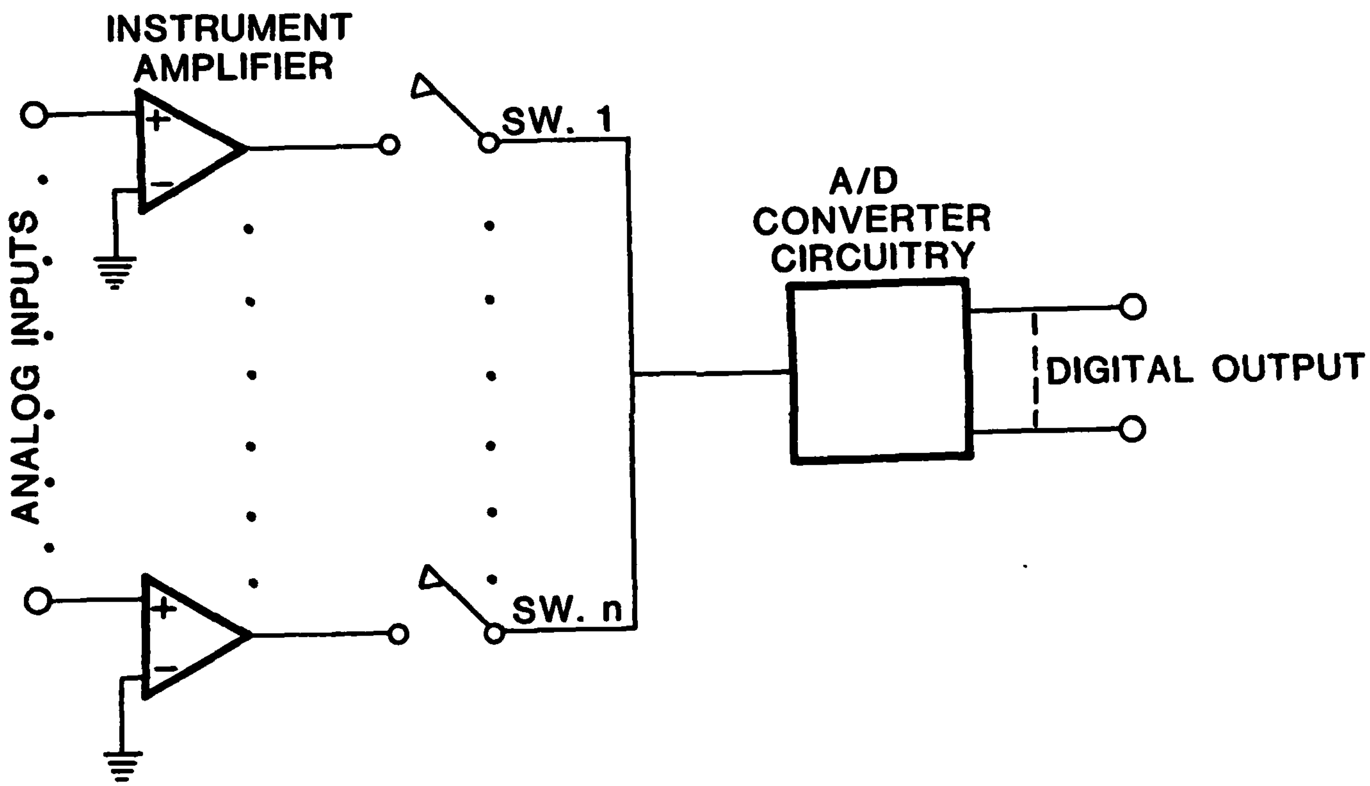


Figure 2.13. Modern Instrument Amplifier Configuration.

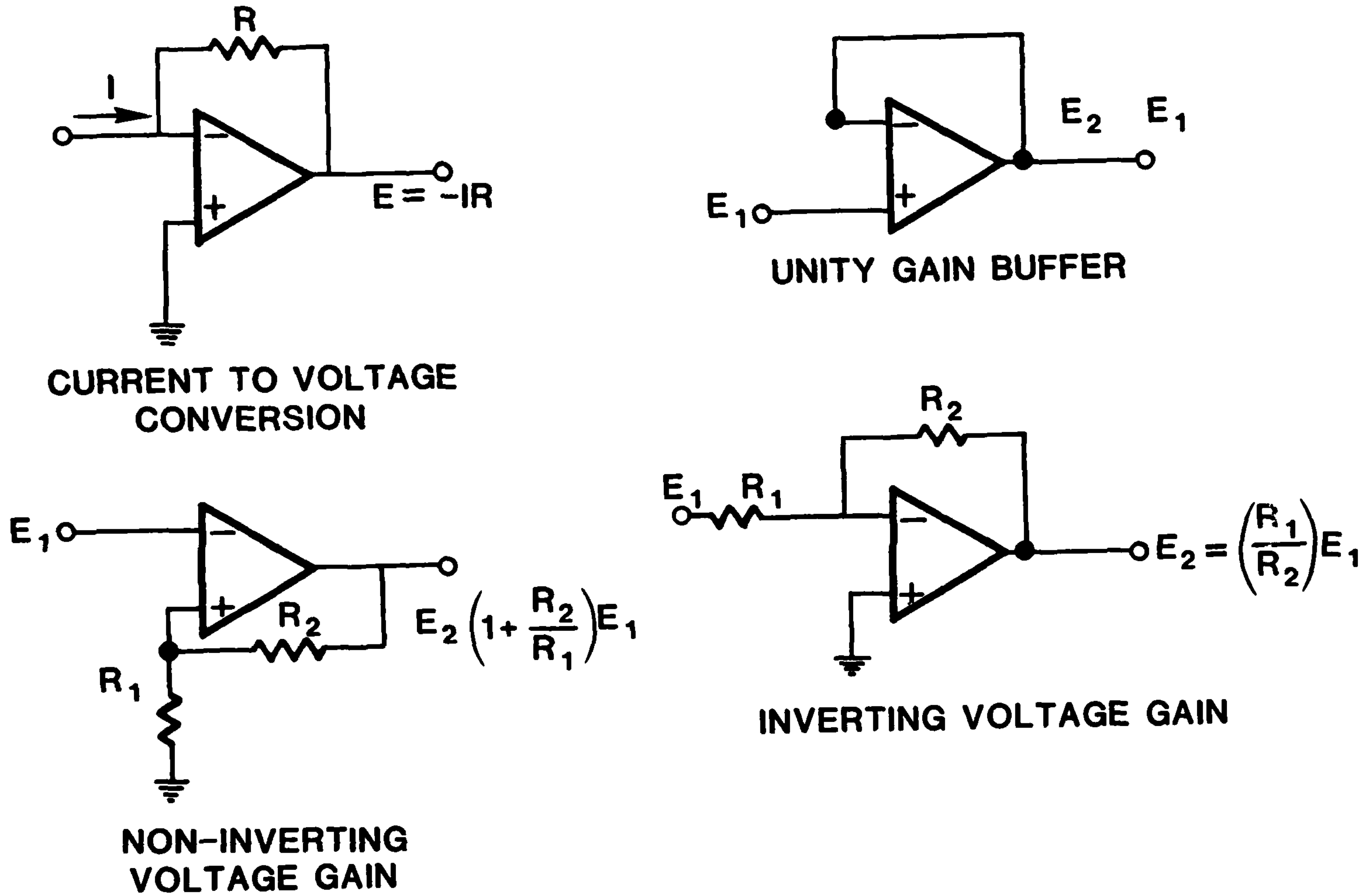


Figure 2.14. Modern Instrument Amplifier Configuration.

is no longer adequate. An instrument amplifier is capable of handling differential inputs plus many other desirable features that do not exist in common operational amplifiers. An instrument amp is a high performance differential amplifier, generally operating with a gain ranging from 0 to 1000, very high input impedance, high common mode rejection, and wide bandwidth for a small settling time. The instrument amplifier's main task is to provide a high level (greater than 0.1 volts), single-ended input for the ADC by amplifying the desired differential-mode signal and rejecting any common mode signals.

To completely understand the meanings of a differential-mode signal and a common-mode signal, they should be defined. A differential-mode signal is defined as the difference between its two inputs. The common-mode input is defined as the average of the two inputs or, in other words, a signal common to both inputs. In many cases, the common-mode signal has a greater amplitude than does the differential-mode signal. Thus, in order to minimize the signal noise, it is important for the amplifier to be able to reject the common-mode signal at some finite level. For example, suppose that a 3 millivolt thermocouple output is riding on a 10 volt common-mode voltage. If the amplifier has a common-mode rejection (CMR) of 80 dB, then the common-mode voltage introduces a 1 milli-volt error in the temperature measurement.

Even though the instrument amp is a precision device, there are different kinds of errors associated with it that should be considered. Some of the errors are inherent to the instrument amp, and others are caused by faulty applications. An instrument amp's gain is selected so that the amplified signal is in the upper half of the ADC input range, so that maximum use of the ADC's resolution can be utilized. In some applications, such as that in Fig. 2.12 (where one instrument amp handles many analog inputs), the amplitude range for each input may not be the same. This results in the amplified signal not meeting or exceeding the input signal range of the ADC. This problem can be remedied by providing an instrument amp for each channel, as is illustrated in Fig. 2.13.

Errors that are inherent to instrument amplifiers are that they exhibit gain errors and nonlinearity, as Fig. 2.15 greatly exaggerates. A gain error is the difference between the desired gain and the actual slope of the fitted line. These errors are dependent upon the particular gain of the amp and range from 0.01 to 0.5 percent of full scale. Instrument amplifiers also tend to drift somewhat with temperature and time. There are ways to implement instrument amplifiers in the circuit to minimize these sources of errors. The user of an instrument amp should first evaluate the maximum amount of each of the above errors that is acceptable in the interface design and then choose the amp that best fits.

Another type of amplifier that has applications in signal conditioning is the isolation amplifier; and, generally, it is placed before the instrument amplifier in the circuit. Isolators are intended for applications requiring safe, accurate measurement of d.c. and

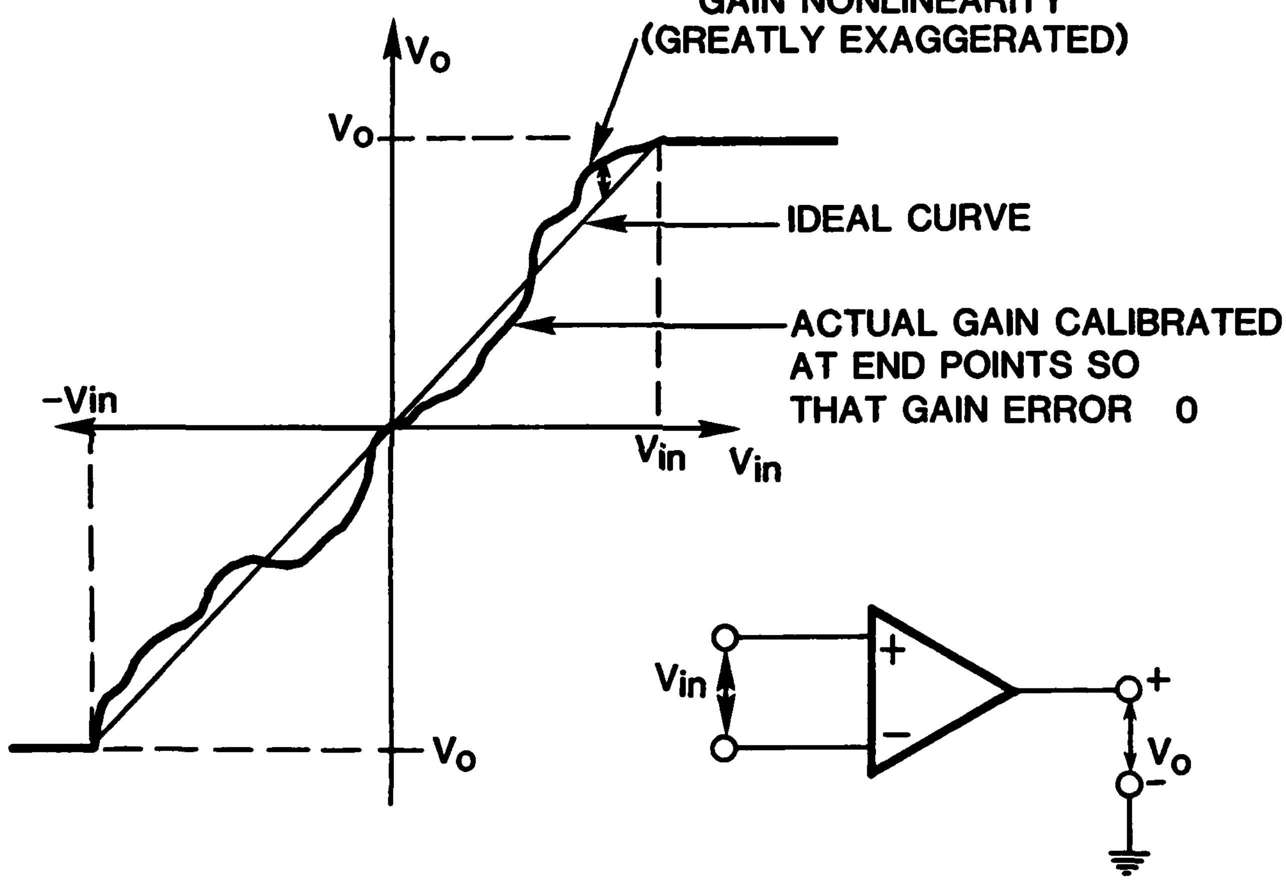


Figure 2.15. The Gain Errors and Nonlinearity of Amplifier.

low-frequency voltage or current in the presence of high common-mode voltage (perhaps thousands of volts) with high common-mode rejection. They also have applications where safety is important in general-purpose measurements and where d.c. and line-frequency leakage must be maintained at levels well below certain required minimum levels. These applications are in electrical environments of the kind associated with medical equipment, conventional and nuclear power plants, automatic test equipment, industrial process control systems, and field-portable instrumentation.

Any non-conducting medium may be used to achieve isolation (such as light, ultrasonics, and radio waves). The most widely used form of isolation (because of its low cost *and ease of implementation*) is transformer coupling of a high-frequency carrier for communicating power to and signals from the input circuit.

When the amount of drift with temperature and time is a critical specification, then chopper amplifiers have an application in signal conditioning. Choppers have the lowest drifts with temperature and time of all the different amplifier types. A typical value for maximum temperature drift is about $0.1\mu V/°C$. A non-inverting chopper amplifier is an op-amp in which the d.c. offset between the feedback point and the input modulates a high frequency carrier. The modulated carrier, then a.c.-amplified and demodulated, produces an offset corrected d.c. output level. Most chopper amplifiers are unbalanced, single-ended-input devices; that is, the input and output voltage share a common terminal.

This appears to inhibit the chopper's ability to take a differential measurement across a bridge, as an instrument amp can. But, if the bridge circuit is excited from a floating source (no common connection to ground) such as a battery, dc-to-dc converter, or an ac signal coupled through a transformer, then the output can be viewed as floating with respect to the excitation source. This means there would be no common-mode voltage presented to the amplifier, thus yielding very low drift and high common-mode rejection.

Filters

In every signal conditioning interface circuit, a certain amount of noise or interference will be present in the circuit, no matter what steps are taken to reduce its magnitude. Since, with low level, inputs to the system may be over-shadowed by the noise (causing errors in the signal), steps such as filtering should be taken. For most sensors used in fluid power applications, the information is at a relatively low frequency as compared to most noise; therefore, it can be easily filtered.

This section will discuss the various filtering techniques and filter circuits.

The most useful type of filter is the low-pass filter. Low-pass means that signals with frequencies less than a critical cut-off frequency are passed without attenuation and signal frequencies greater than the critical cut-off frequency will be greatly attenuated to a point, for all practical reasons, of nonexistence. As was stated earlier, the signal frequencies produced in fluid power applications will be relatively low and the frequency of the noise and interference is relatively high; therefore, a low pass filter provides a more than adequate job of filtering all the noise from the sensor signal.

The simplest low-pass filter consists of a resistor and a capacitor connected as illustrated in Fig. 2.16. The resistor-capacitor, low-pass filter is a passive device (no power supply required), where the more commonly used low-pass filter is an active device (requiring power supply) utilizing operational amplifiers. Figure 2.17 illustrates two typical first-order RC (registor-capacitor), active low-pass filters. There are many other circuit configurations that produce higher order filters than those shown; but, for the purpose of this section, they will be omitted.

Besides reducing the noise, filtering is also used to reduce the bandwidth, so that any frequency components greater than 1/3 to 1/2 the

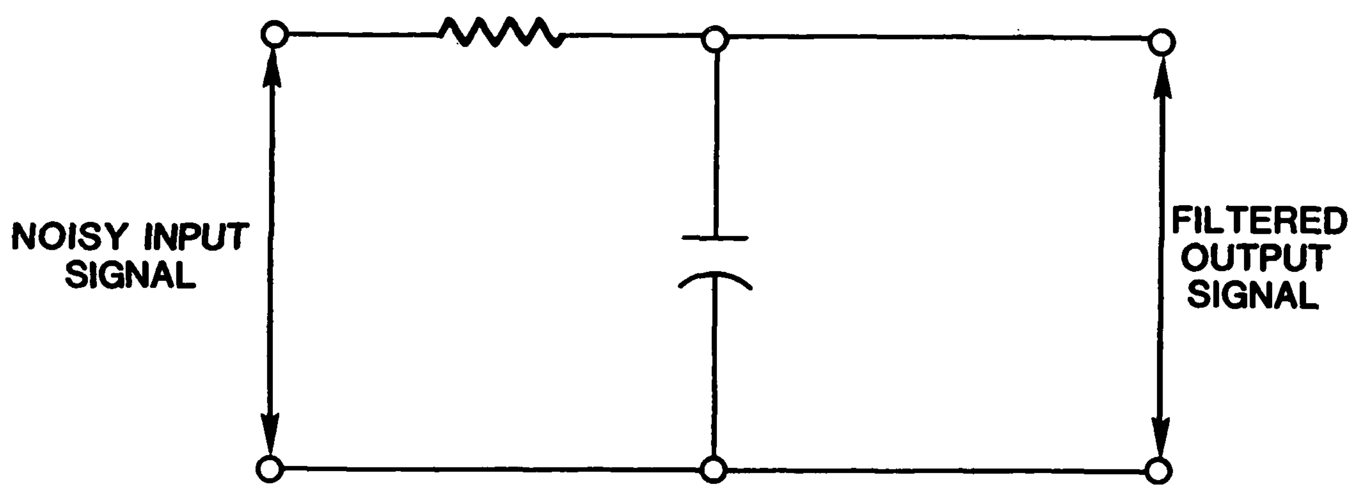


Figure 2.16. Low Pass Filter Circuit.

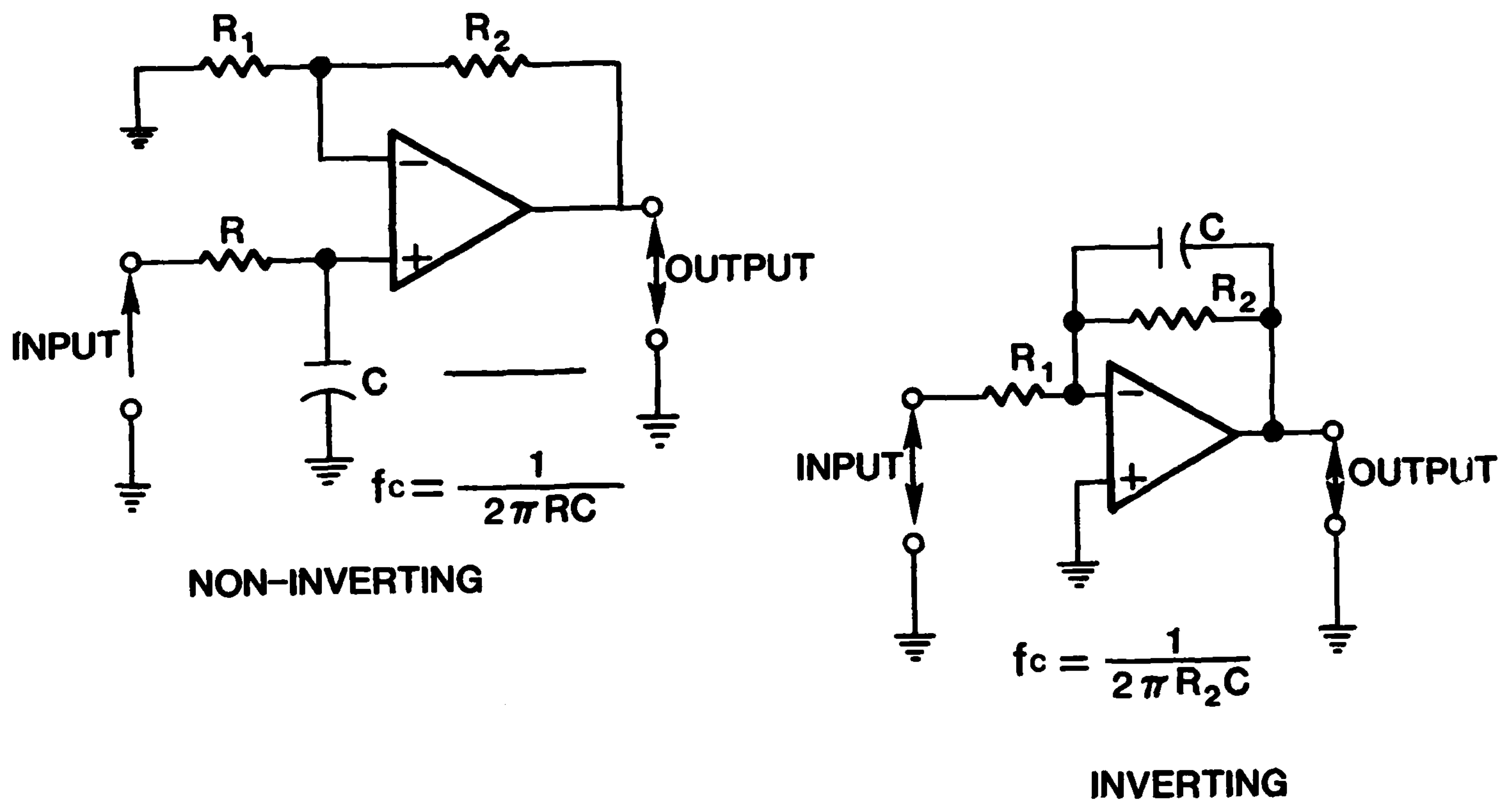


Figure 2.17. Active Low Pass Filter Circuit.

sampling rate in sampled-data systems are neglected, as is termed necessary by sampling theory. Many volumes of texts have been published devoted to the subject of passive and active filtering and should be used by the sensor user if a more detailed understanding of filtering is required.

Analog Multiplexers

A multiplexer is an array of switches with a common output connection for selecting one of a number of analog inputs. The switches may be either mechanical or electronic devices. Most commonly they are electronic, with several methods of implementation. The different electronic multiplexers are solid-state devices such as bipolar junction transistors, junction-field-effect transistors (JFET'S) or metal-oxide-semiconductor field-effect transistors (MOSFET's). Each has distinct advantages and disadvantages over the others. Each type will be briefly discussed in this section along with the design considerations of each.

Bipolar transistors were used in some of the first electronic multiplexers because they were the first type of transistors to be developed. Compared to the current types of transistors, bipolar transistors have no advantages and are seldom used in multiplexing applications. The disadvantages that make them impractical to use are that they have inherent offset voltages and are difficult to drive.

MOSFETs and JFETs are often used in multiplexers where the maximum signal range is between +15 and -15 volts. The on-resistance of these devices ranges from 5 to 1000 ohms, and the off-resistance can exceed 10 gigaohms. Although multiplexers built from MOSFET and JFET devices are commonly used, they exhibit special problems in system applications. If the power to the multiplexer is turned off, the devices all tend to turn on. The reason for this is because they require a negative voltage (with respect to common) to turn off, and a lack of it (as is the case with a power loss) will turn them on. This problem has been overcome with added circuitry and complexity, and a discussion of the required additions is beyond the scope of this section.

Unlike the amplifier stage(s) and filtering stage(s), multiplexing is an optional stage whose use is left up to the discretion of the designer. If many analog signals are to be sampled and can have the ADC in common, then the use of a multiplexer may make sense. But, if a single channel is used, then no added advantage would be realized from the use of a multiplexer. As is the case with any added stage in the signal conditioning system, noise non-linearities and other undesirable effects may result with the addition of the multiplexer stage.

Sample & Hold Techniques

The basic function of a sample-and-hold in the signal conditioning system is to capture a sample of the analog signal and hold it constant during the conversion time of the ADC.

The simplest hold circuit is a capacitor placed across the signal source to be sampled. To effectively retain an accurate value of the signal, the capacitor must be as large as possible. Because there is always some resistance in the circuit, there is a finite amount of time associated with charging the capacitor to the signal level; and, the larger the capacitor, the longer the charge up time. This is the greatest disadvantage in using capacitors as a hold device.

Currently, op-amps are used as sample-hold circuit devices. By their use, the problems encountered with capacitors are eliminated.

Analog to Digital Converters (ADC)

An ADC is the heart of the digital data acquisition system. It is a device that takes an unknown continuous analog input-signal and converts it into a three-bit binary number which can easily be manipulated by a computer. The n-bit binary number is a binary fraction representing the ratio between the unknown input signal voltage and the ADC's full-scale voltage reference.

A three-bit converter would have a binary range of from 000 to 111, corresponding to an analog signal range of from 0 volts to the maximum reference voltage. A change of one binary bit corresponds to some finite signal voltage change. Figure 2.18 illustrates the relationship between the input signal to the ADC and the digital binary output. As can be seen, there is a small amount of error in the conversion because there is a range of the input that is between two binary numbers. The higher the number of binary bits used to represent the analog signal,

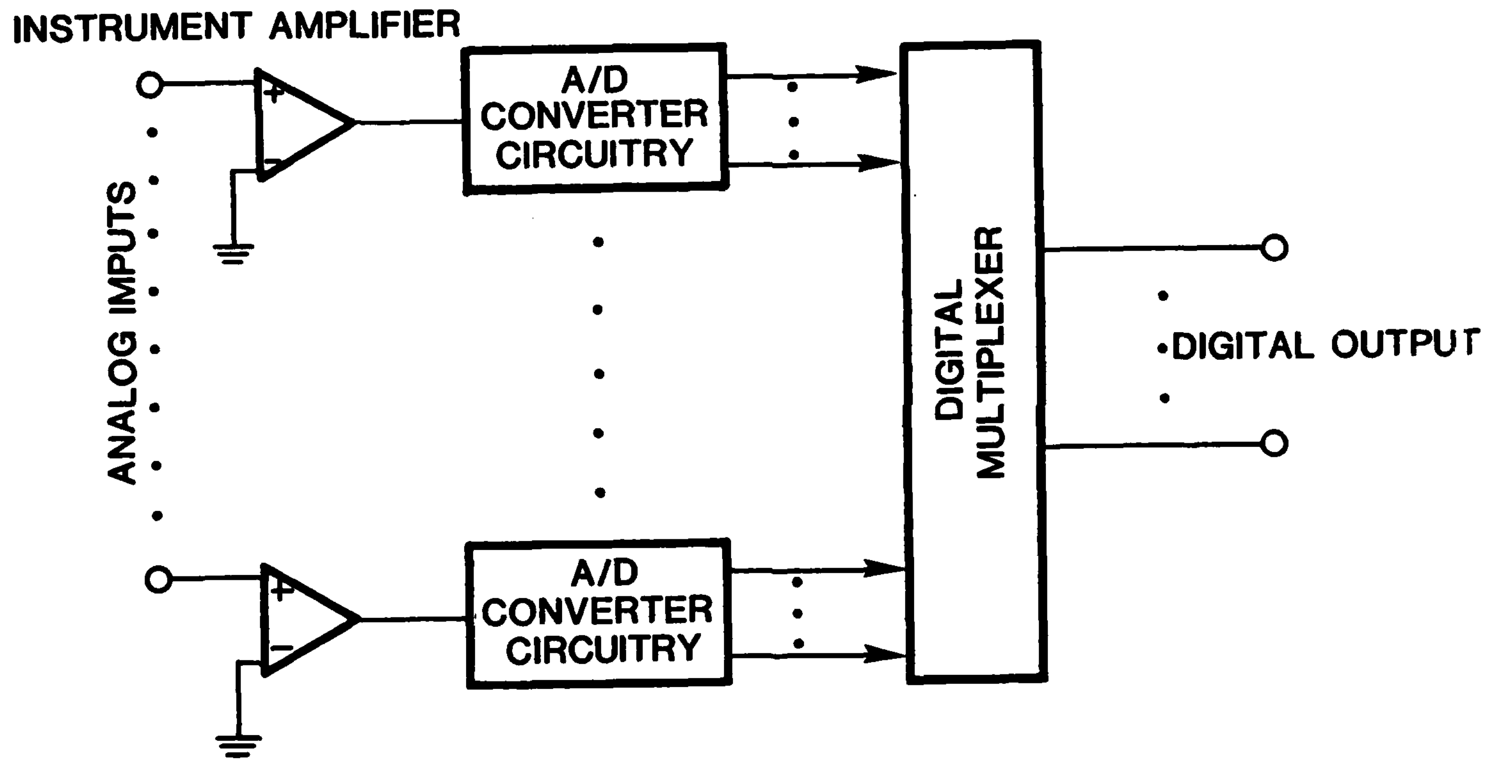


Figure 2.18. Amplifier - A/D Converter Circuit.

the smaller is the quantization error.

There are several different techniques used to convert the analog signal to a digital representation. The most popular will briefly be discussed in the remainder of this section.

Counter-ramp converter. One of the simplest ways of implementing A/D conversion is to use a Digital-to-Analog converter (DAC) in conjunction with a counter and comparator. The counter counts from 0 to the maximum bit number in binary progression, and the DAC takes these counts and converts them to an analog signal. The analog signal generated by the DAC is then compared to the unknown input signal by a comparator. If the two signals are equal, the counter is stopped and the current count is the binary representation of the input signal. Figure 2.19 shows a variation of the counter converter, which is a tracking counter ADC. Instead of counting up from 0 to the signal level with an up counter, an up-down counter is used to count up or down, depending upon whether the DAC analog signal must increase or decrease to reach the input signal.

Successive approximation converter. The successive approximation converter uses a much more efficient strategy for varying the reference input to the comparator. It requires only n-comparisons maximum for an n-bit converter.

A "binary search" is carried out by the converter to find the best

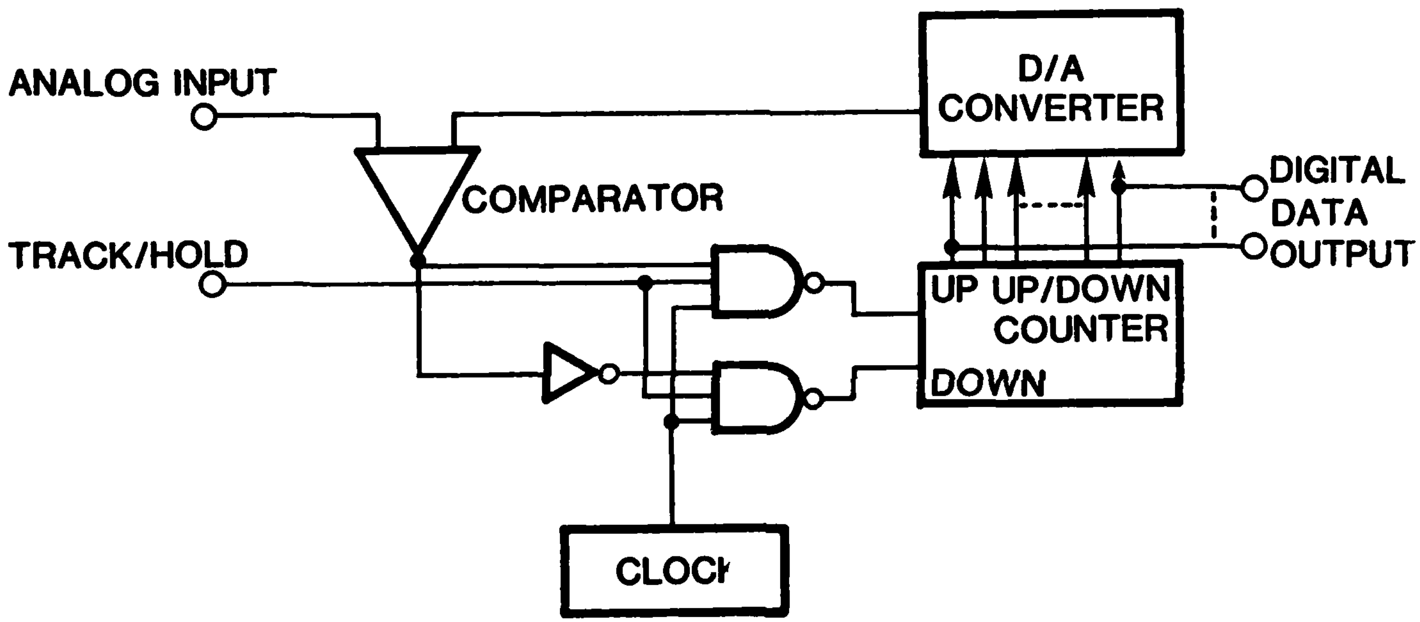


Figure 2.19. Tracking Counter Type AD Converter.

approximation for the +0 input. The successive approximation circuitry sets the DAC to 1/2 the full scale value and checks the comparator output. If the comparator output is 1, the DAC is incremented by 1/4 full scale and decremented by 1/4 full scale if the comparator output is 0. This process continues until n-approximations have been made. Figure 2.20 illustrates the internal logic of a successive approximation ADC.

Dual Slope Converter. This type of converter is very popular in data acquisition systems and solves many of the conversion problems associated with other types of converters.

Figure 2.21 illustrates the typical internal logic of a dual-slope converter. The conversion cycle consists of two separate integration intervals. The unknown signal voltages are first integrated for a known interval of time, and this value is compared to a known reference voltage, which is integrated over a variable length of time. Conversion of the input begins when the unknown input is switched to the integrator input and, at that same time, a counter begins to count until it reaches overflow. The control circuitry then switches the negative reference to the integrator input and integrates it until the output is back to zero. At that time, the counter is turned off. The counter contains the binary value for the input. Figure 2.22 illustrates the integrator output and time relationships.

Parallel (Flash) Converter. These are the fastest converters available. To gain the speed of conversion sometimes necessary in data

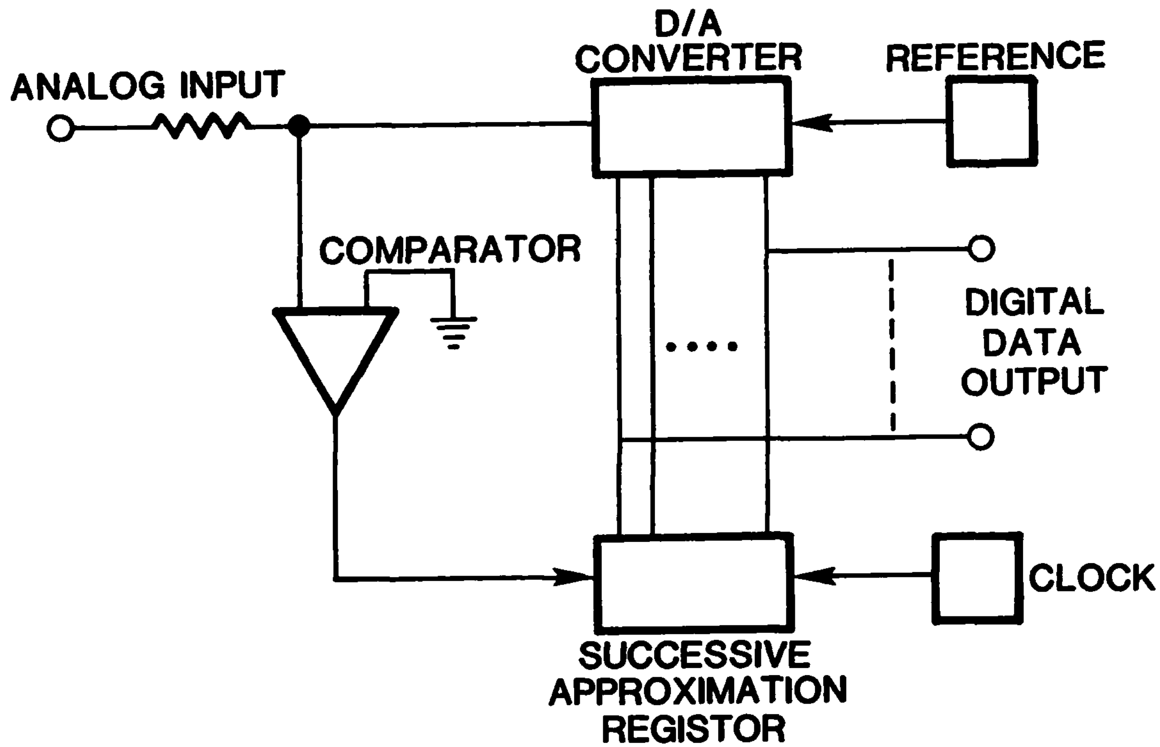


Figure 2.20. Successive Approximation AD Converter.

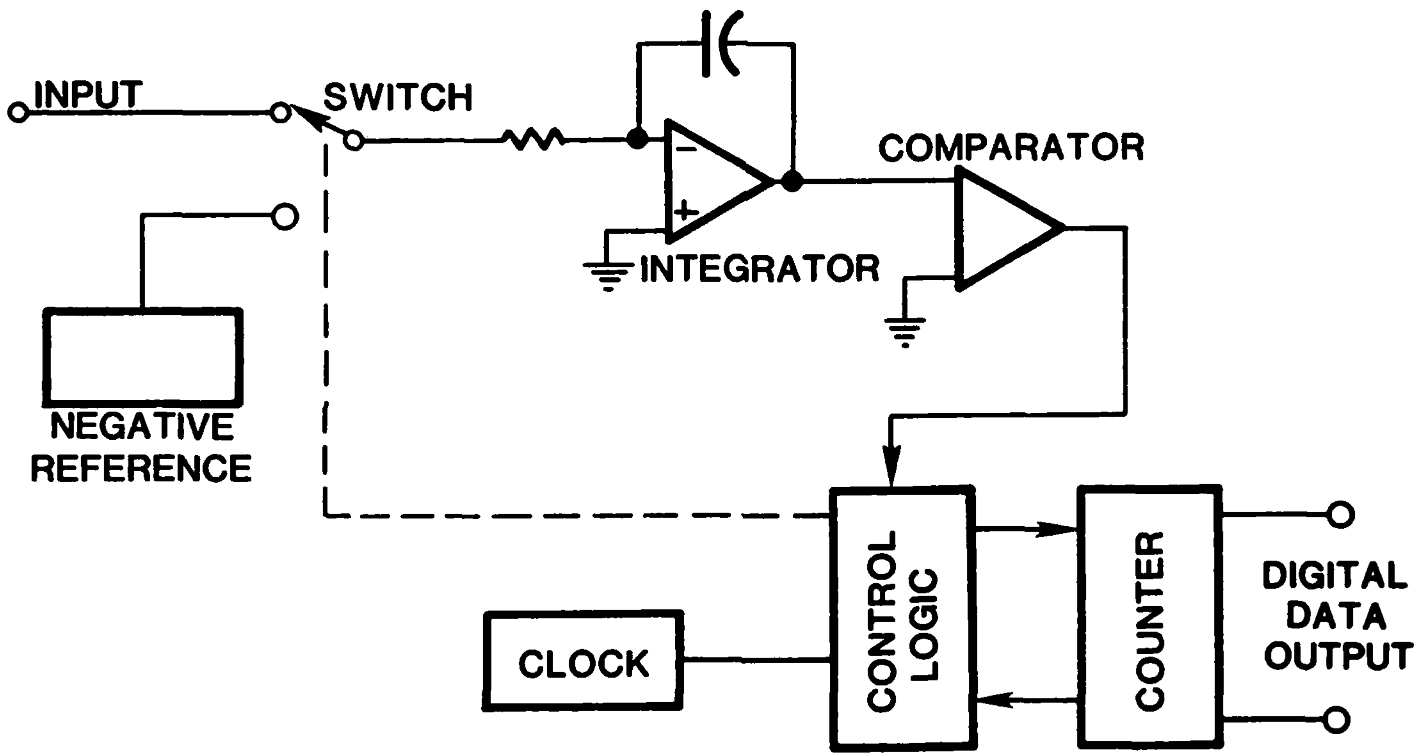


Figure 2.21. Dual Slope AD Converter.

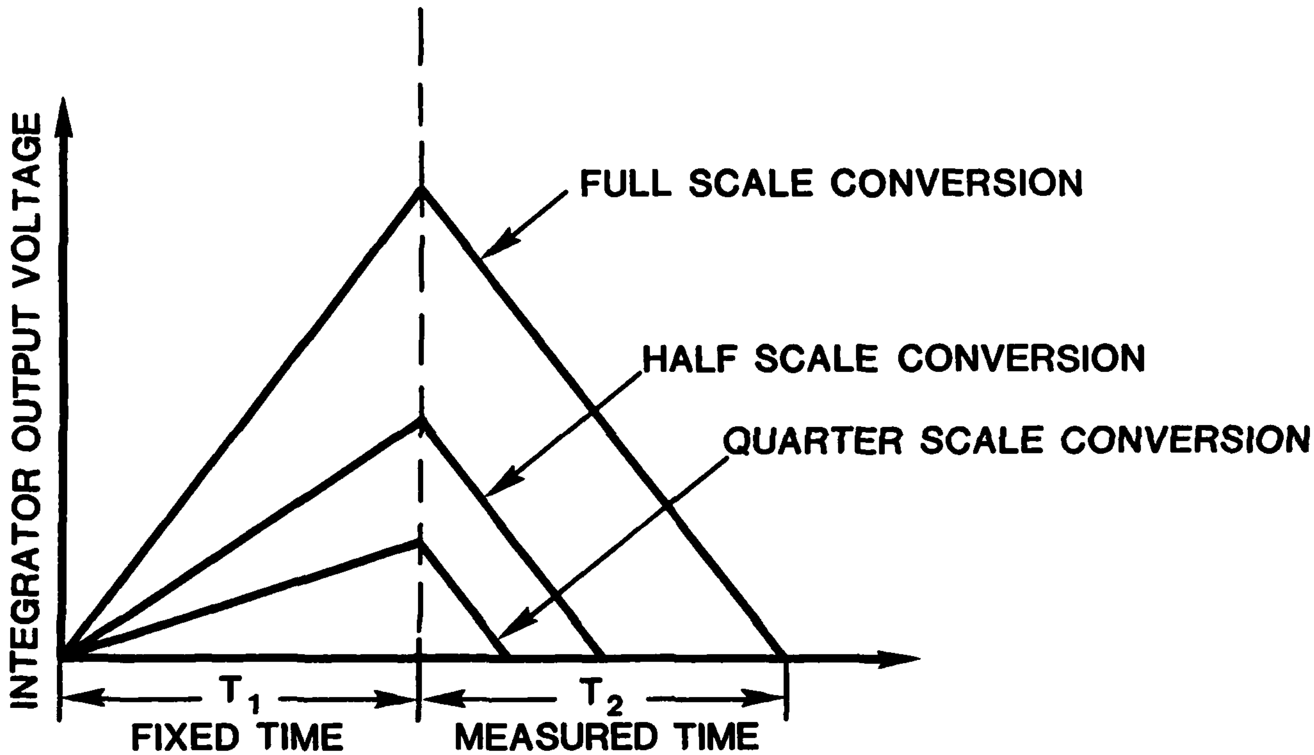


Figure 2.22. Output Waveform for Dual Slope AD Converter.

acquisition systems, much extra hardware is required to implement the converter. Figure 2.23 shows a typical configuration of a flash converter. The input signal voltage is simultaneously compared to 2^n-1 reference voltages by 2^n-1 comparators. The only time delays are those due to the comparator and logic circuitry, so the digital output can follow the varying analog input with only a small delay.

The cost of implementing this type of converter is the only limiting factor because, as the resolution (number of bits) increases, the number of components increases by 2^n-1 with n-bit resolution.

GENERALIZED PERFORMANCE AND CHARACTERISTICS

The performance characteristics of parameter measurement devices are critical to their application. These characteristics include:

* Measurand
* Electrical
* Static
* Dynamic

The measurand characteristics are concerned with the response of the sensor to only a specific measurand. This does not mean that other measurands cannot be derived from known relationships to the sensed quantity. However, it must be agreed that, for every measurement, the measurand must be stated in terms of the designated sensor.

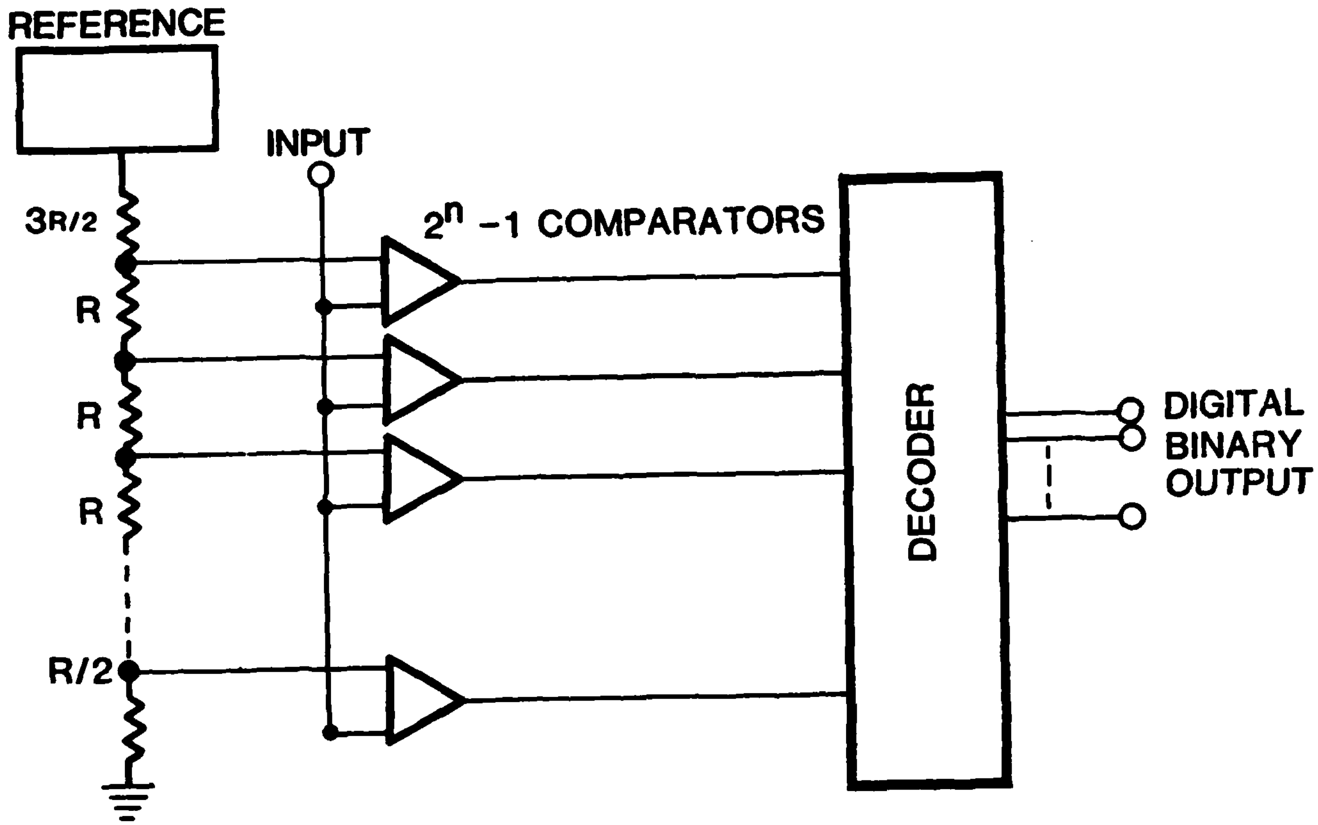


Figure 2.23. Parallel (Flash) AD Converter.

Electrical Characteristics

Excitation is the external electrical voltage and/or current applied to a sensor for its proper operation. Excitation is needed for all active type sensors -- not for passive or self-generating types. The excitation is generally stated in terms of d.c. or a.c. voltage or of a current applied to the transducer.

Output is the electrical quantity produced by a sensor which is a function of the applied measurand. The output is usually a continuous function of the measurand (analog output) in the form of current, voltage ratio, or voltage amplitude or a variation of other parameters such as capacitance or inductance. Analog output can also be in the form of frequency. Digital output sensors produce an output that represents the magnitude of the measurand in the form of discrete quantities coded in a system of notation.

End points are the output values at the upper and lower limits of the sensor's range. They may be the result of a single calibration cycle, or they may be the average of end point readings obtained from consecutive calibration cycles. A tolerance is usually applied to end points.

Impedance has somewhat the characteristics of resistance, in that it is a measure of the extent to which the circuit impedes the flow of current; it has the same units as resistance -- namely, ohms. Sensor output as well as excitation is affected by transducer and load impedances, as illustrated in Fig. 2.24. The impedance measured across the excitation terminals is the input impedance and across the output terminals is the output impedance of the sensor. The impedance presented to the sensor's output by the associated external circuitry and transmission lines is the load impedance. Mismatching of the output impedances can cause a loading error in the output. This error increases with the ratio of output impedance to load impedance.

Demodulators and amplifiers in sensor electrical circuits share some undesirable characteristics which must be minimized -- an a.c. component (ripple). These undesirable characteristics include random disturbances originating in the amplifier components and modifying the output (noise), changes in the characteristics of the component which result in output variations (gain instability), and the time which elapses between the removal of an overload applied to the sensor (causing the amplifier to limit and distort) and the restoration of the output to a value which is again within specified limits (recovery time). This sort of distortion in a sensor's sinusoidal (a.c. output, in the form of harmonics other than the fundamental component) is the harmonic content of the output. It is usually expressed as a percentage of the root mean square (rms) output.

Grounding and insulation characteristics of a sensor circuit are critical to its proper operation. The excitation ground and output ground may be isolated from each other or connected together as a single ground (common ground). Both grounds are usually isolated from the

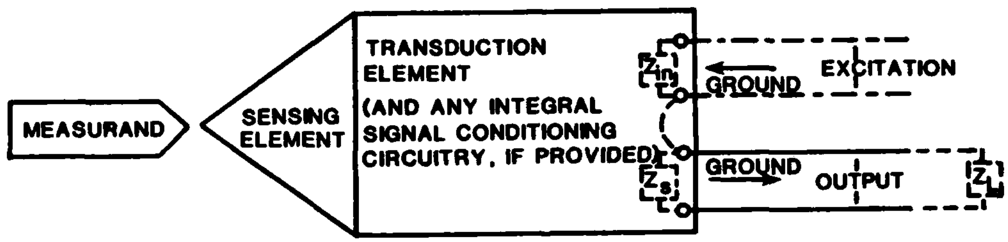


Figure 2.24. The Electrical Characteristics of the Sensor.

transducer's case (floating ground). When two or more portions of a transducer are electrically insulated from each other, the resistance between the portions is the insulation resistance. The degree of insulation can also be expressed in terms of the voltage applied across the mutually insulated portions which causes arcing or conduction between them (breakdown voltage). The breakdown voltage rating always refers to the maximum voltage which can be applied without causing arcing or conduction between specified insulated portions of a sensor.

Static Performance

It is important that static performance characteristics of a sensor be understood if sensor selection is to be addressed. Performance assessment is integrally related to the method of test; hence, one cannot be divorced from the other. Static performance characteristics concern accuracy related terms of the sensor. The method of test described herein will hopefully illustrate and clarify the sensor accuracy terms.

The accuracy of the referenced standard shall preferably be no greater than 1/10 the tolerance allowed for the sensor, but in no case greater than 1/3 the allowed tolerance. If 1/10 or less, the accuracy rating of the referenced standard may be ignored. When the accuracy rating of the reference is between 1/10 and 1/3 that of the test sensor, the accuracy rating of the reference shall be taken into account.

The deviation plot is the difference between observed and the corresponding ideal output expressed as a percent of ideal output span, and this plot serves as the basis for making the accuracy assessment of a sensor. The percent deviation is usually plotted versus input or ideal output. When plotted versus percent input, a positive deviation denotes that the observed value is greater than the ideal output value. The deviation plot is obtained as follows:

1. Precondition the test sensor and stabilize under steady-state operation conditions.
2. Maintain test conditions throughout the test.
3. Vary the input for one full range traverse in each direction -- starting at mid-range.
4. Observe and record output values for at least five input points.
5. Determine the difference between the observed and ideal output values.
6. Express the difference as the deviation -- a percent of ideal output span.
7. Plot the deviation versus percent input.
8. Positive deviation means observed output is greater than the ideal output.

The measured accuracy is defined as the maximum deviation of upscale and downscale traverses and is determined directly from the deviation values or the deviation plot. The accuracy is expressed as a plus and minus percent of ideal output span.

Dead band is the portion of the range between actuation in the increasing and decreasing direction of the measurand. It is determined using the following procedure:

1. Precondition sensor and maintain test condition.
2. Slowly vary input (up or down) until a detectable output is observed.
3. Slowly vary the input in the opposite direction until the output change is observed.
4. Dead band is the increment through which the input is varied.
5. Repeat at a number of points to confirm maximum dead band.

The dead band is expressed as a percent of the input span.

<u>Drift</u> is an undesired change in output over a period of time, which change is not a function of the measurand. The drift point is defined as the maximum change in output during a standard test period. The procedure for drift point is as follows:

1. Precondition the sensor and maintain test conditions.
2. Adjust the input to the desired value without overshoot and record the output.
3. Maintain the input and operating conditions constant.
4. After the designated test period, record the output.

The drift point is expressed as a percent of the output span for the specified test period. The point drift is the maximum change in recorded output value observed during the test period and is expressed in percent of ideal output span for a specified time period.

Hysteresis is the maximum difference in output at any measurand value within the sensor's range when the value is approached first with increasing and then decreasing measurand. Hysteresis incorporates both friction error and dead band and can be determined directly from the deviation values. This is done by determining the maximum difference between corresponding upscale and downscale outputs. The actual hysteresis is the remainder after dead band is subtracted. It is expressed as a percent of ideal output span. The effects of friction error can be determined by dithering the sensor -- i.e., applying intermittent or oscillatory acceleration forces to it -- during use and during calibration. This can be seen in the graph shown in Fig. 2.25.

Linearity is the closeness of a calibration curve to a specified straight line and is taken as the deviation of the average curve from a straight line defined as:

1) A line connecting zero and the full-scale input points (end points).
2) Best-fit straight line through the average deviation points that minimize the deviation.

The procedure to determine linearity is as follows:

1. Plot the average deviation curve of response.
2. Draw a line connecting the end point to zero and the best-fit line.
3. Determine the maximum deviations between average curve and both lines. See Figs. 2.26 and 2.27.

Linearity is expressed as the percent of full scale (% FSO) or, for

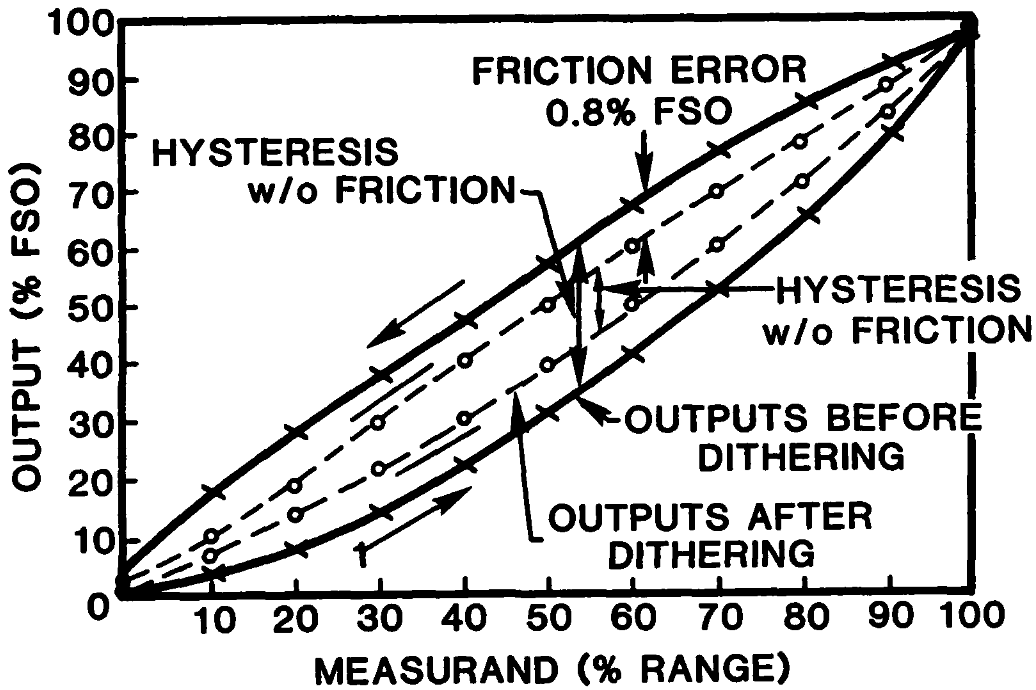


Figure 2.25. Hysteresis with Friction.

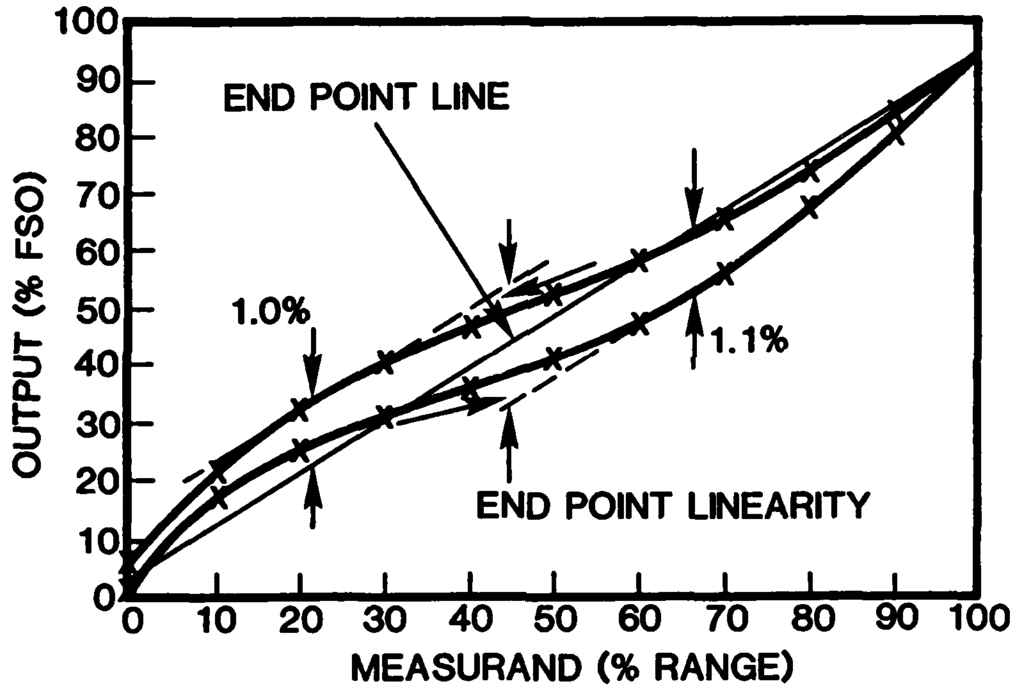


Figure 2.26. End Point Linearity Curve.

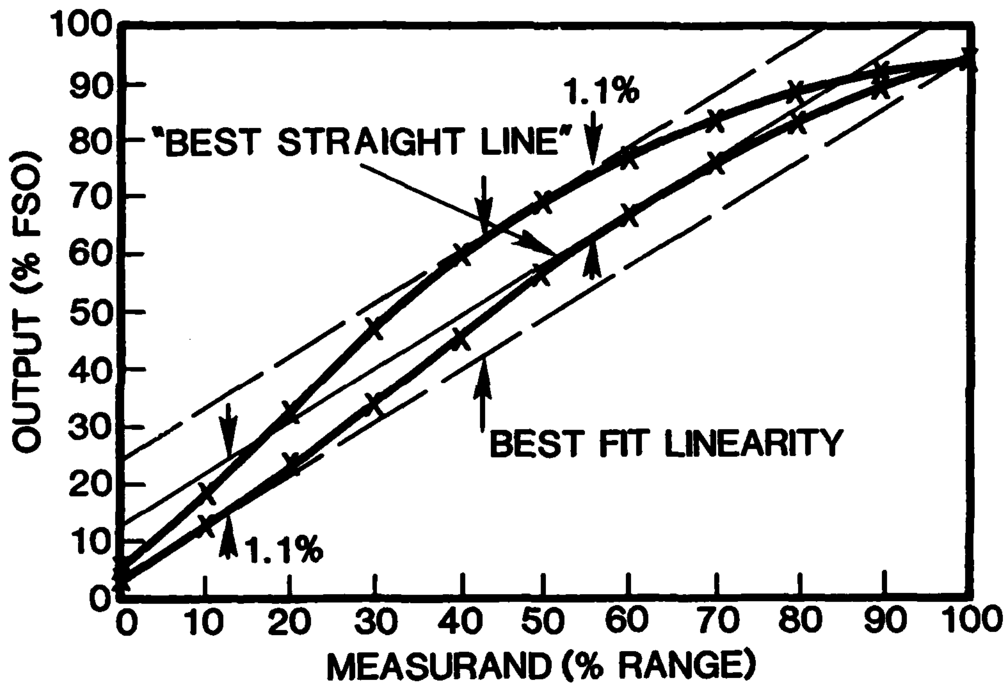


Figure 2.27. Best Fit Linearity Curve.

potentiometric sensors, as the percent voltage ratio (% VR) for both End Point Linearity or Best Fit Linearity. It is not easy to determine linearity precisely. Limitations are imposed by the accuracy of the calibration instruments and by the repeatability of the instrument under test. The value of linearity assigned to an instrument cannot be better than the repeatability.

Repeatability is the ability of a transducer to reproduce output readings when the same measurand value is applied to it consecutively, under the same conditions, and in the same direction. It is defined as the closeness of agreement among a number of consecutive output measurements for the same applied (magnitude and direction) input. Repeatability is determined by applying the following procedure:

1. Obtain a number of consecutively derived deviation curves having the same operating conditions.
2. Observe the maximum difference of upscale and downscale outputs.
3. Determine the maximum difference from either the upscale or downscale curve, which is reported as the repeatability and is expressed in terms of percent of output span. (See Fig. 2.28.)

Two types of repeatability are recognized: short-term and long-term, or drift. Short-term generally refers to a test time of the order of minutes, while long-term repeatability tests may occur over a period ranging from days to months.

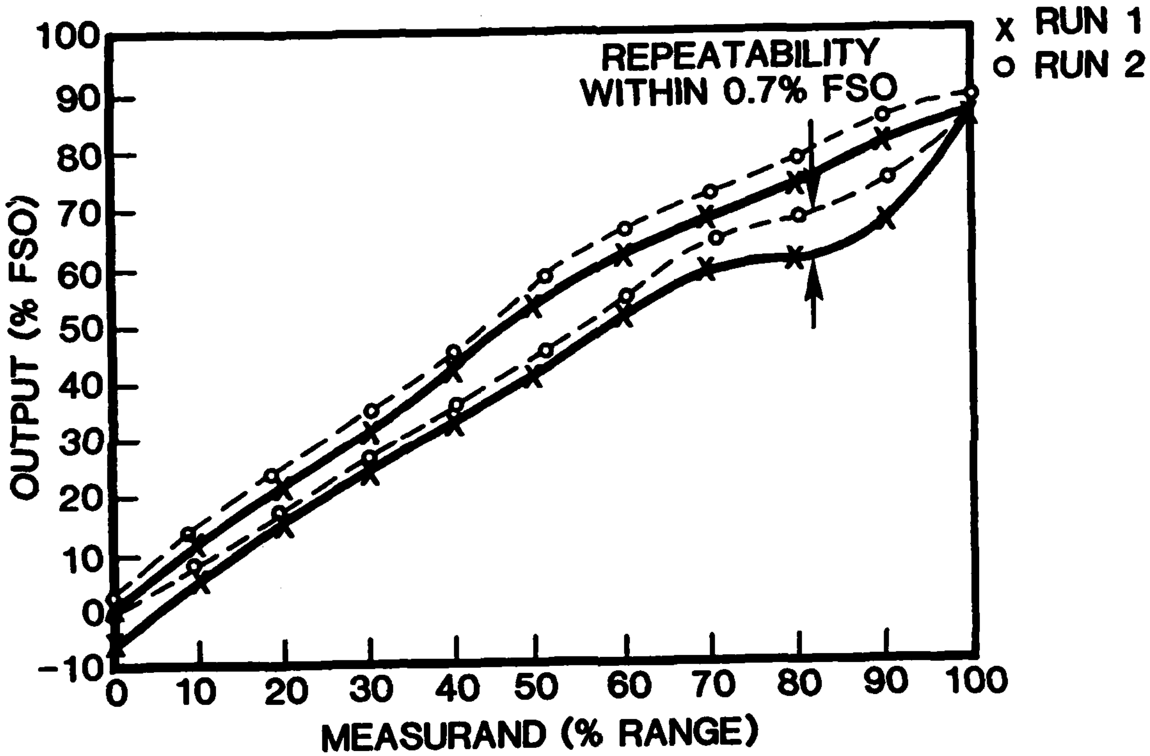


Figure 2.28. Repeatability Curve.

Reproducibility is defined as the maximum difference between recorded output values taken at different times, by different technicians or in different facilities. It is the closeness of agreement among repeated measurements of the output for the same value of input made under the same operating conditions over a period of time, approached from both directions. Reproducibility includes hysteresis, dead band, drift and repeatability. The procedure for determining reproducibility is as follows:

1. Obtain a number of deviation plots for the same inputs.
2. Prepare an average curve to represent both upscale and downscale readings.
3. At a different time or situation, repeat Steps 1 and 2.
4. Maximum difference in the curves is the reproducibility.

Reproducibility is expressed as the percent of output span per specified time, operator or facility.

Resolution is the magnitude of output step changes (expressed in percent of full-scale output) as the measurand is continuously varied over the range. It is a measure of output smoothness and is particularly noticeable in the output of potentiometric transducers which use wirewound elements. The magnitude of these output step changes expressed in % FSO is the resolution of the sensor. Resolution is not equal throughout the sensor's range but varies slightly from step to step.

Since resolution is a measure of the degree to which small increments of the measurand can be discriminated in terms of sensor output, that is the smallest change in applied stimulus that will produce a detectable change in the sensor output; it is commonly expressed as maximum resolution (the greatest of all steps), Fig. 2.29. To avoid this expression of "maximum step," the concept of average resolution has been considered by many. Average resolution is defined as the reciprocal of the total number of sensor output steps over the measuring range, multiplied by 100 and expressed in percent of full-scale output.

Conformance is the closeness of a calibration curve to a specified curve. The most common type of conformance is theoretical-curve conformance, where the specified curve can be defined by a table, a graph, or an equation. The calibration curve (average of upscale and downscale readings) from a specified theoretical curve is so positioned as to minimize the maximum deviations -- see Fig. 2.30. This freedom to position the curves relative to each other must be revealed by defining it as "independent conformance" to the specified curve.

Dynamic Performance

In machine applications, it is often desirable to establish the ability of a sensor to follow a rapidly varying measurand; e.g., where step changes in measurand level have to be monitored. Many sensors, such as accelerometers and rate gyros, react dynamically in a manner similar to that of an ideal second-order physical system (mass, damping, spring). In such cases, the specification of frequency response, response time and damping is very appropriate.

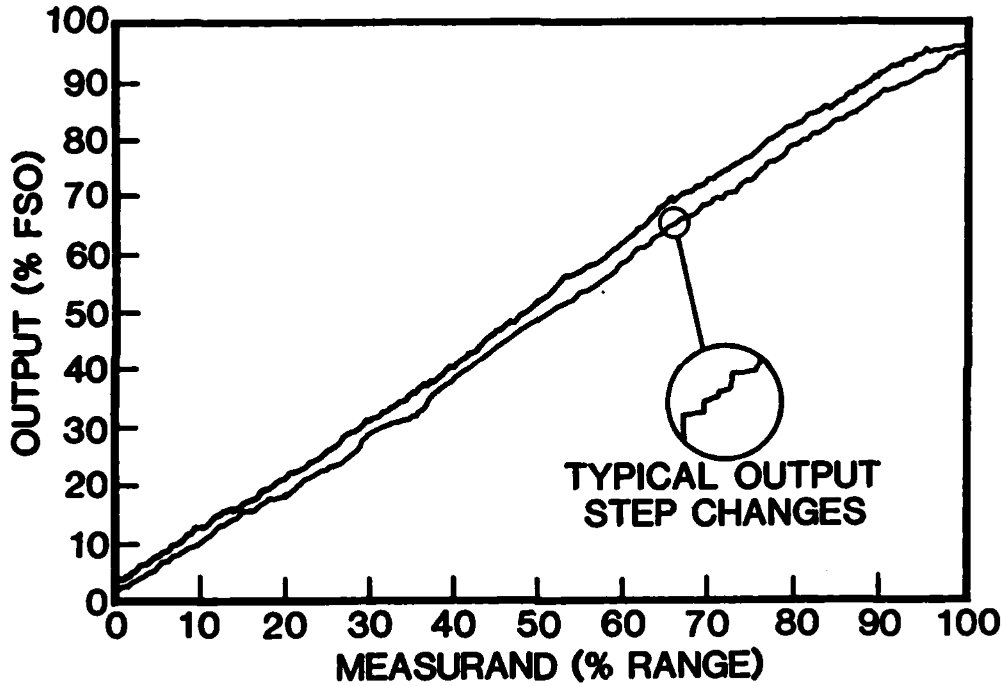


Figure 2.29. Resolution Curve.

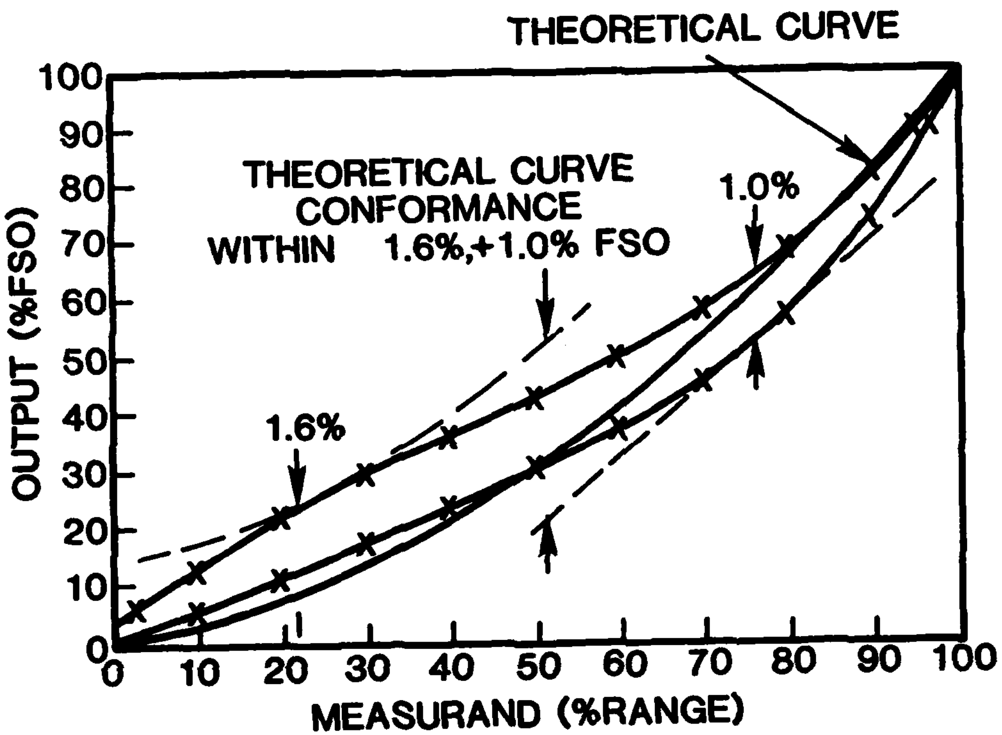


Figure 2.30. Conformance Curve

Frequency response is the change with frequency of the output/measurand amplitude ratio (and of the phase difference between output and measurand) for a sinusoidally varying measurand applied to a sensor within a stated range of measurand frequencies. In this instance, the measurand varies sinusoidally, and the typical response curves for a static and dynamic sensor (Curve A) and for a dynamic sensor only (Curve B) are shown in Fig. 2.31. A time difference always exists between output and measurand variations. The output lags behind the measurand and, if this phase shift is significant to the measurement, the frequency response can be stated in terms of the phase difference between output and measurand. The response curves in Fig. 2.31 deal with the amplitude ratio of output to measurand -- when this ratio drops, the output is not tracking the measurand.

Response time is the length of time required for the output of a sensor to rise to a specified percentage of its final value as a result of a step change of the measurand. The time required for the corresponding output change to reach 63% of its final (steady) value is the time constant of a sensor. The time required to reach a different specified percentage of this final value (e.g., 90, 98, or 99%) is the response time of the sensor -- See Fig. 2.32. The time in which the output changes from a small to a large specified percentage of the final value is the rise time.

Damping is the energy dissipating characteristic which, together with natural frequency, determines the limit of frequency response and

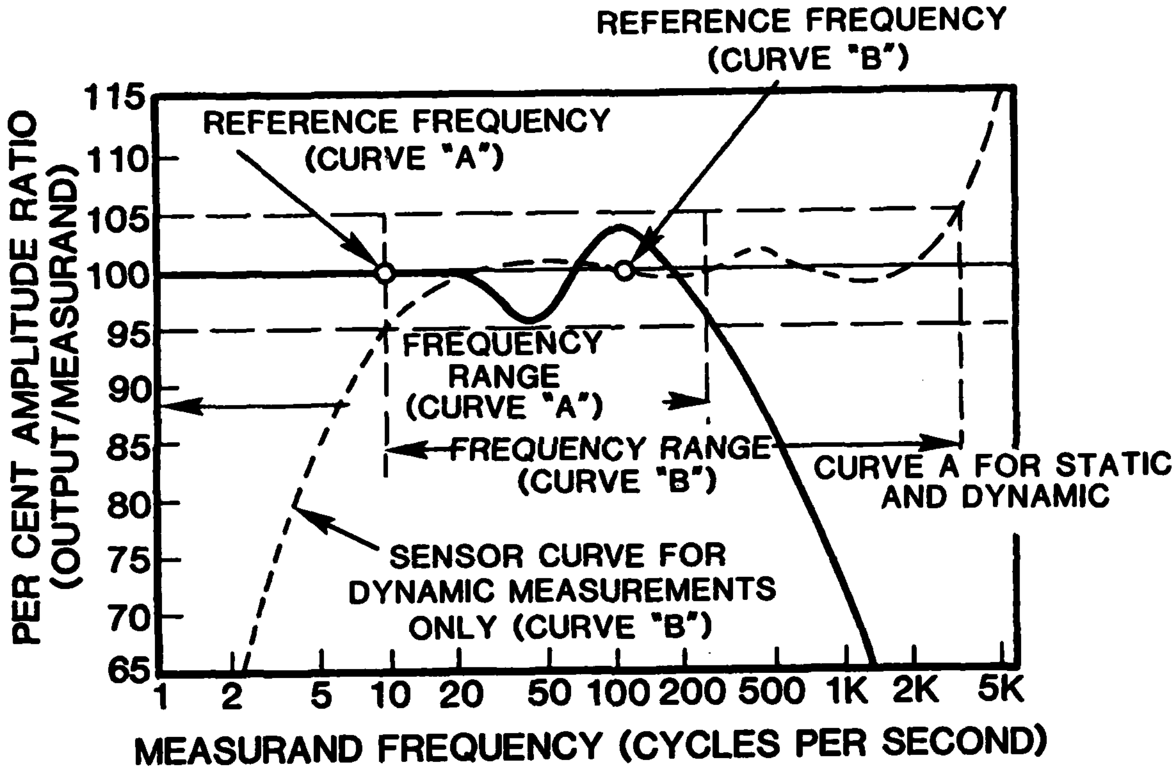


Figure 2.31. Frequency Response Curve.

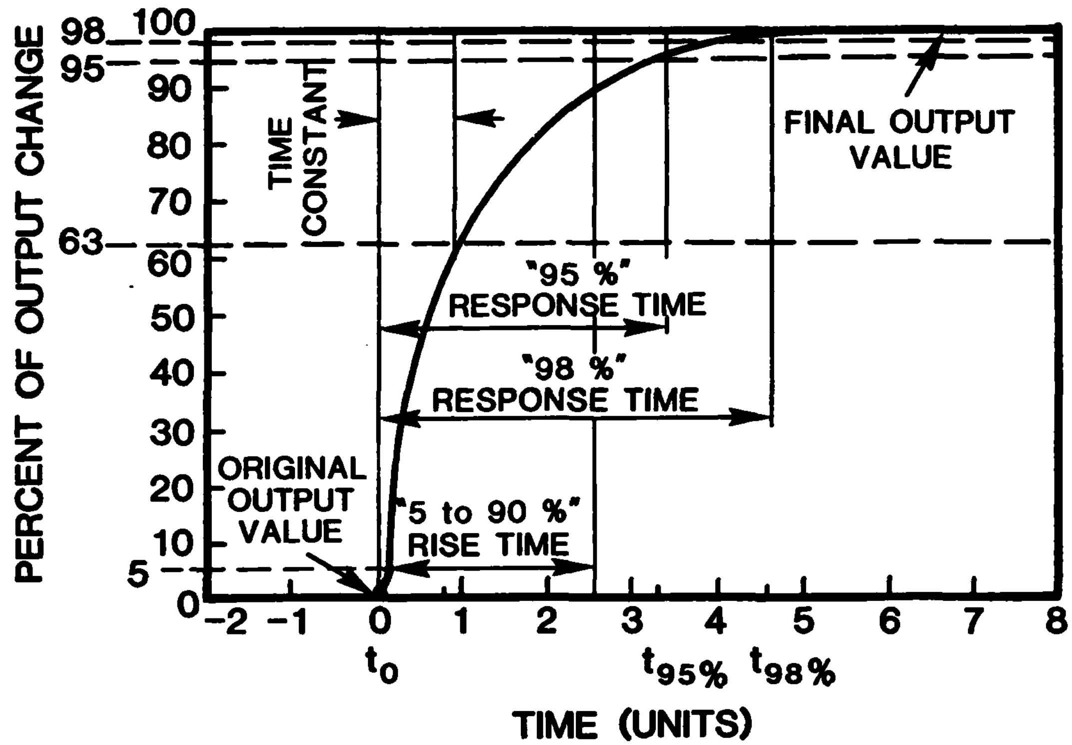


Figure 2.32. Dynamic Response Curve.

the response time characteristics of a sensor. An underdamped system oscillates about its final steady value before coming to rest at that value; and, an overdamped system comes to rest without overshoot, and a critically damped system is at the point of change between the underdamped and the overdamped conditions. The energy-dissipating properties or damping of a sensor determines its upper limit of frequency response and its response-time characteristics. Fluid-damped sensors may be affected by temperature changes which change the viscosity of the damping fluid. If an increase in temperature would decrease the size of the passages through which the damping fluid must pass, the change in viscosity would be compensated, and the damping would remain unchanged.

The most significant characteristics of signal processors and modifiers are those relating to gain, offset, bias current, and common-mode rejection. Each of these areas will be covered in the following paragraphs.

Gain range is the range of gain which the manufacturer states that the device will perform and still meet the other specifications. A typical range would be between 0 and 1000. Although specified at a specific range, the device may work at a much higher gain but may fail the other specification ranges and therefore make using high gains impractical or unwise.

Gain accuracy is the specification describing the amount of deviation of the actual gain and that calculated from the gain equation.

Trimmers can be used to compensate for the gain error elsewhere in the overall signal conditioning system.

Nonlinearity is the deviation from a straight line on a plot of output vs. input. The magnitude of linearity error is the maximum deviation from the "best straight line," with the output swinging through its full-scale range. The amount of nonlinearity is expressed as a percentage of full-scale output range.

Voltage offset can be initially set to zero but can change with temperature and time and thus will create errors. A maximum value for the offset range is generally specified by the manufacturer of the device.

Common-mode rejection is a measure of the change in output when both inputs are changed by an equal amount. The common-mode rejection is generally specified for a full-range, common-mode voltage change at a given frequency and specified source impedance imbalance.

The fundamental aspects of parameter measurement devices have been presented. With this background, the user is well prepared to develop the selection methodology of parameter measurement devices and complete the specification sheets.

CHAPTER III

SPECIFICATION AND SELECTION OF PARAMETER MEASUREMENT DEVICES

GENERAL CONSIDERATIONS

This chapter presents the specification and selection methodology for parameter measurement devices. It covers the sensors used for each measurand. Each section addresses a particular measurand arranged in alphabetical order. The contents of each section are presented in a uniform manner in order to help facilitate information retrieval for those who have studied the material. Specifically, the order of presentation in each measurand section is as follows:

* Measurand and Associated Terms
* Measurand Units
* Measurand Sensing Methods
* Sensor Selection Criteria
* Specification Sheet

In addition to the discussion of sensors, specification sheets for signal modifiers and processors (amplifiers, filters, and monitors) are also developed and included for assisting in the selection and procurement of parameter measurement system components.

ACCELERATION SENSORS

Measurand and Associated Terms

Acceleration -- time rate of change of velocity with respect to a reference point.

Oscillation -- variation of the magnitude of a quantity which is periodically changing directions.

Vibration -- a mechanical oscillation.

Damping -- an energy-dissipating characteristic which brings a system to rest when the input is removed.

Shock -- transient excitation of a mechanical system.

Jerk -- time rate of change of acceleration with respect to a reference system.

Mechanical Impedance -- force to velocity ratio during simple harmonic motion (ability of system to resist vibration).

Measurand Units

Linear Acceleration -- g or gravity = 32.2 ft/s^2

Angular Acceleration -- $radians/s^2$

Shock and Vibration -- g units

Jerk -- g per sec

Frequency -- hertz where 1 Hz = 1 cycle per second (cps)

Sensing Methods

The seismic mass (proof mass) is the sensing element common to all acceleration sensors. The principle of operation is that, when an acceleration is applied to the case of the sensor, the mass within moves relative to the case. When the acceleration stops, a mass restraining mechanism returns the mass to its original position.

Spring Acceleration Sensor -- An acceleration applied to the case causes the mass to try to remain stationary, resulting in a force being applied to the spring in a direction opposite to the applied acceleration. This force causes the spring to compress an amount proportional to the acceleration.

Piezoelectric Acceleration Sensor -- The applied acceleration to the case causes the mass to try to remain stationary, resulting in a force being applied to the crystal. This force on the crystal results in a voltage being generated by the crystal proportional to the acceleration.

Capacitance Acceleration Sensor -- An applied acceleration to the case results in the mass trying to remain stationary, thus causing the distance between the movable and stationary plate to vary. Varying the distance between the two plates causes the capacitance between the plates to vary corresponding to the level of acceleration.

Electromagnetic Acceleration Sensor -- An acceleration applied to the case results in the mass trying to remain stationary, thus causing a motion of the magnet relative to the coil. This motion causes a voltage to be generated across the coil corresponding to the value of the acceleration.

Sensor Selection Criteria

Frequency response and range are the main factors in selection of accelerometers. Applications require a frequency range over which a flatness of response within plus or minus 5 percent from a low reference frequency on a Bode Plot (amplitude-frequency diagram) must be obtained. In general, piezoelectric accelerometers must be used when the frequency range needed exceeds 400 Hz. Acceleration ranges between plus or minus one and plus or minus 100 g can be provided by all types of accelerometers.

Piezoelectric accelerometers have wider temperature ranges than any other types. Transducers with integral semi-conductor circuits have inherent temperature limitations.

Specification Sheet

The specification sheet for acceleration sensors is presented in Table 3.1.

ATTITUDE SENSORS

Measurand and Associated Terms

Attitude -- relative orientation of an object.

Attitude Planes -- orthogonal reference axes normally designated as pitch, yaw and roll axes (the conventional x, y and z axes, respectively).

Attitude Sensors -- measures inclination relative to three references axes.

Attitude Rate Sensors -- measures time rate of change of attitude.

Bearing -- direction given by the angle in the horizontal plane between a reference line and the line between the reference point and the point whose bearing is specified (usually measured clockwise from

Table 3.1. Acceleration Sensor Specification Sheet.

ACCELERATION SENSOR SPECIFICATIONS

APPLICATION
- SPECIFIC MEASURAND: ______
- SENSOR TYPE: ______
- SYSTEM I.D.: ______
- TRANSDUCTION PREFERENCE: ______

MECHANICAL DESIGN
- CASE DIMENSIONS: L ______ W ______ H ______
- MOUNTING: ______
- IDENTIFICATION: ______
- CASE CONSTRUCTION: ______
- SENSOR WEIGHT: ______
- MOUNTING FORCE/TORQUE: ______
- TRANSDUCTION ELEMENT: ______
  - Complete Following, If Applicable
- CASE ALIGNMENT/SENSING AXIS: ______
- LOCATION OF CENTER OF SEISMIC MASS: ______
- DAMPING METHOD/FLUID: ______
- ISOLATION OF CRYSTAL: ______

ELECTRICAL DESIGN
- ELECTRICAL CONNECTOR: ______
- CALIBRATION PROVISIONS: ______
- ALLOWABLE LOAD IMPEDANCE: ______
  - Complete Following, Where Applicable
- INSULATION RESISTANCE: ______
- BREAKDOWN VOLTAGE: ______
- INPUT IMPEDANCE: ______
- OUTPUT IMPEDANCE: ______
- EXCITATION VOLTAGE: ______
- EXCITATION CURRENT OR POWER DRAIN: ______
- FREQUENCY OF A–C EXCITATION: ______
- MAXIMUM EXCITATION: ______
- CONNECTOR–PIN I.D.: ______
- GROUNDED/UNGROUNDED CRYSTAL: ______
- OUTPUT CAPACITANCE: ______
- OUTPUT RESISTANCE: ______
- INSULATION RESISTANCE: ______
- SENSOR CABLE DESCRIPTION: ______

PERFORMANCE CHARACTERISTICS
- ACCELERATION: RANGE ______ OVERLOAD ______
  - Complete Following, Where Applicable
- STATIC ERROR BAND: ______
  - (Specify Reference as Best Fit or End Point)
- CREEP: ______ MOUNTING ERROR: ______
- TRANSVERSE SENSITIVITY: ______
- OVERLOAD OUTPUT: ______
- STABILITY (long term): ______
- RESOLUTION: ______
- FRICTION ERROR: ______
- SENSITIVITY: REFERENCE ______ STRAIN ______
- AMPLITUDE LINEARITY: ______
- FREQUENCY RESPONSE: ______
- DAMPED NATURAL FREQUENCY: ______
- DAMPING RATIO: ______
- MOUNTED RESONANCE FREQUENCY: ______

ENVIRONMENTAL CHARACTERISTICS
- OPERATING TEMPERATURE RANGE ______
- TEMP.: ERROR BAND ______ SENSITIVITY ERROR ______
- THERMAL: ZERO SHIFT ______ SENSITIVITY SHIFT ______
- DAMPING RATIO CHANGE WITH SYSTEM: ______
- ELECTROMAGNETIC INTERFERENCE LIMITS: ______

RELIABILITY CHARACTERISTICS
- LIFE: STORAGE ______ OPERATING ______

the reference line).

Measurand Units

Units are angular degrees, minutes, and seconds, rarely radians for attitude and bearing.

Units for attitude rate are angular units per unit time, usually degrees per second.

Sensing Methods

The attitude reference systems provide a convenient means of categorizing attitude sensing methods -- the nature of the reference system relative to the orientation of the body of interest. The conventional reference systems are -- Inertial, Gravity, Magnetic, Flow Stream and Optical. The four most common attitude sensors are discussed below.

Single Degree of Freedom Gyroscope Attitude Sensor -- The spin axis of the rotor is the reference to which the attitude of the case is compared. If the attitude of the case is disturbed, an attitude change of the case results -- an angular displacement between case and gimble shaft. This sensor is only able to detect changes in attitude about one axis other than the spin axis.

Two-Degree-of-Freedom Attitude Sensor -- This sensor is able to detect an attitude change about two axes other than the spin axis. An attitude change results in a deflection about an axis perpendicular to the spin axis and the axis about which the attitude change occurred.

Resistance Attitude Sensor -- The angle of tilt determines the position of the air bubble which establishes the amount of the resistive electrode in the electrolyte. This causes the resistance at the leads to change corresponding to the angle of tilt or inclination.

Tilt Switch Attitude Sensor -- When the sensor is horizontal, an open circuit exists between the center (common) electrode and each of the end contacts. When tilted, the mercury completes the circuit between the common electrode and one of the end electrodes, while an open circuit remains between the opposite end electrode and the common electrode.

Sensor Selection Criteria

The time period during which attitude measurements must be obtained is one of the primary selection factors. The time for spin-motor runup or uncaging can be critical. Other factors of importance include the allowable drift during the measuring period, other accuracy characteristics, the dynamics of the measurand, and cost. Of course, the characteristics and functions of the measuring system to which the sensor is connected and of the nature of the mission during which measurements are made are all significant.

Specification Sheet

The specification sheet for attitude sensors is presented in Table 3.2.

Table 3.2. Attitude Sensor Specification Sheet

ATTITUDE SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ____

SENSOR TYPE: ____

SYSTEM I.D.: ____

TRANSDUCTION PREFERENCE: ____

MECHANICAL DESIGN

CASE DIMENSIONS: L ____ W ____ H ____

MOUNTING: ____

IDENTIFICATION: ____

CASE CONSTRUCTION: ____

CAGING TYPE/ACCESS: ____

ELECTRICAL CONNECTIONS: ____

ANGULAR SPEED: ____

ANGULAR FREEDOM: ____

LOCATION OF STEPS: ____

DESCRIPTION OF DAMPING: ____

OTHER: ____

ELECTRICAL DESIGN

ELECTRICAL CONNECTORS: ____

EXCITATION VOLTAGE: ____

EXCITATION CURRENT OR POWER DRAIN: ____

EXCITATION FREQUENCY AND PHASING: ____

CURRENT: STARTING ____ RUNNING ____

IMPEDANCE: INPUT ____ OUTPUT (load) ____

CAGING: VOLTAGE ____ CURRENT ____

INTEGRAL HEATERS: ____

INSULATION FESISTANCE: ____

ELECTRICAL CAGE DESCRIPTION: ____

PERFORMANCE CHARACTERISTICS

ATTITUDE RANGE (each axis): ____

FULL SCALE OUTPUT: ____

ZERO–MEASURAND OUTPUT: ____

LINEARITY: BEST FIT ____ END POINT ____

HYSTERESIS (% FSO): ____

REPEATABILITY (% FSO): ____

RESOLUTION (% FSO): ____

FRICTION ERROR (% FSO): ____

THRESHOLD: ____ DRIFT: ____

ERROR BAND (% FSO): ____

DYNAMIC DRIFT RATE: ____

TIME PERIODS: RUN–UP ____ RUNDOWN ____

WARM–UP ____ CAGING ____ UNCAGING ____

ERRECTION ____

MECHANICAL ALIGNMENT: TOLERANCE ____

FREQUENCY RESPONSE: ____ TIME CONSTANT: ____

DAMPING RATIO: ____ NATURAL FREQ.: ____

ENVIRONMENTAL CHARACTERISTICS

AMBIENT TEMP./THERMAL SHOCK: ____

VIBRATION, SHOCK & ACCELERATION: ____

OTHER: ____

RELIABILITY CHARACTERISTICS

LIFE: STORAGE ____ OPERATING ____

DISPLACEMENT SENSORS

Measurand and Associated Terms

Position -- location relative to reference point.

Displacement -- change in position with respect to reference point (linear or angular).

Proximity -- relative closeness of two points.

Distance -- relative separation of two points.

Motion -- a changing displacement.

Measurand Units

Linear Displacement -- inches, centimeters, feet, meters, micro-inches, mils (milli-inches) or millimeters.

Angular Displacement -- degrees, or radians.

Sensing Methods

The two types of displacement sensors are:

Contactless-sensing -- with a light beam or electromagnetic type sensors, and

Contact sensing -- using a sensing shaft connected to object. Hence, with the exception of the few contactless-sensing types, the sensing shaft and associated couplings represent the basic means for measuring displacement. Since the output of a displacement sensor indicates the position of the sensing shaft and not the actual driving point, to make the two the same, the integrity of the coupling and sensing shaft are important.

Strain Gauge Displacement Sensor -- The displacement of the sensing shaft causes the cantilever beam to bend. This puts a strain on the top gauge in tension and a strain on the bottom gauge in compression. A relationship exists between the displacement and the two measured strains.

Optical Angular Displacement Sensor -- The rotation of the slotted-hole disk through the optical detector assembly causes a number of pulses to be produced. The number of pulses corresponds to a given angular displacement. The counter circuitry counts the number of pulses.

Photoconductive Potentiometer Displacement Sensor -- The displacement of the shutter determines the position of the light bar on the sensor. The light bar acts as a non-contact wiper of the sensor. The variable output voltage is proportional to the position of the light bar.

Variable Reluctance Displacement Sensor -- The displacement of the movable armature causes the air gap to change, thus changing the reluctance of the magnetic circuit. This change in reluctance causes a change in the inductance of the coil. A change in the coil inductance corresponds to a change in displacement.

Variable Geometry Inductive Displacement Sensor -- Changing the length of the coil changes the amount of magnetic flux linkage between the loops of the coil, thus changing the coil inductance. A change in inductance in the coil corresponds to a change in displacement.

<u>Variable Capacitance Displacement Sensor</u> -- By varying the displacement of the movable teeth, the area in common between the movable teeth and the adjacent fixed teeth will vary. The varying of the area will cause the capacitance between the toothed plates to vary corresponding to the displacement.

<u>Variable Capacitance Displacement Sensor</u> -- By varying the displacement of the movable dielectric material between the two fixed plates, the capacitance between the plates will vary. The change in capacitance corresponds to the displacement of the dielectric material.

<u>Variable Capacitance Displacement Sensor</u> -- The displacement of the movable plate causes the mutually common area between it and the fixed plate to change. This change in the area causes the capacitance between the plates to change. The change in capacitance corresponds to a change in displacement of the movable plate.

<u>Variable Capacitance Displacement Sensor</u> -- By varying the vertical displacement of the movable plate, the air gap between it and the fixed plate changes. This change in the air gap causes the capacitance between the plates to change. A change in displacement of the movable plate corresponds to a change in capacitance.

<u>Variable Transformer Displacement Sensor</u> -- By varying the

displacement of the movable secondary coil, the amount of magnetic flux linkage between the stationary primary coil and the movable secondary coil is changed. This causes the output signal to vary in amplitude corresponding to the displacement of the secondary coil.

Variable Inductance Displacement Sensor -- By changing the displacement of the shorting sleeve, the number of turns of the coil effectively in the circuit will change. This changes the inductance in relation to the displacement.

Variable Inductance Displacement Sensor -- By changing the displacement of the movable coil, the amount of magnetic flux linkage between the movable and fixed coil results in a change in the inductance of the sensor. The change in the inductance corresponds to a change in the displacement of the movable coil.

Potentiometer Displacement Sensor -- By varying the displacement of the wiper, more or less turns of the resistive wire are in the circuit. This varies the resistance between the wiper and either end corresponding to the displacement.

Variable Resistance Displacement Sensor -- The position of the movable wiper determines the amount of resistive material which is in the circuit. This position results in varying resistance between the wiper and the end of the material corresponding to the wiper position.

Variable Inductance Displacement Sensor -- The motion or change of displacement of the plate will cause a disturbance in the magnetic field produced by the permanent magnet. This results in a voltage being induced in the coil.

Variable Capacitance Displacement Sensor -- The displacement of the movable plate changes the size of the air gap between the movable and fixed plate. This results in a change in capacitance corresponding to a change in the displacement of the movable plate.

Potentiometer Displacement Sensor -- The displacement of the movable wiper on the resistive wire coil determines the amount of resistance between the wiper and the end of the coil. This acts as a voltage divider when a reference voltage is applied across the ends of the coil. A voltage will be present between the wiper and either end of the coil corresponding to the wiper displacement.

Inductive Thickness Sensor -- The thickness of the test piece changes the reluctance of the magnetic circuit, which results in the inductance of the coil to change. The change of inductance of the coil is related to the thickness of the test piece.

Sensor Selection Criteria

The characteristics of the measuring system in which the displacement sensor is to be utilized are the main selection criteria. These characteristics determine the type of sensor output that is needed and will reduce the number of choices significantly. The sensor range and accuracy are the next most important factors in the selection process. Finally, the characteristics of the measurand must be considered, including the physical requirements for an optimum sensor installation -- this will determine whether a coupled or noncontacting sensor should be used.

Specification Sheet

The specification sheet for displacement sensors is presented in Table 3-3.

FLOW SENSORS

Measurand and Associated Terms

Flow -- fluid in motion.

Flow rate -- time rate of fluid motion (fluid quantity per unit time).

Volumetric flow rate -- fluid volume per unit time.

Mass flow rate -- fluid mass per unit time.

Measurand Units

English units -- gpm for liquids.

Metric -- lpm or lps for liquids.

Sensing Methods

There are three types of sensing elements which respond directly t

Table 3.3. Displacement Sensor Specification Sheet.

DISPLACEMENT SENSOR SPECIFICATIONS

APPLICATION

DISPLACEMENT MEASURAND: ____________

SENSOR TYPE: ____________

SYSTEM: ____________

TRANSDUCTION PREFERENCE ____________

MECHANICAL DESIGN

DIMENSIONS: L ______ W ______ H ______

SENSING SHAFT: ____________

MOUNT: ____________

ELECTRICAL CONNECTIONS: ____________

EXTERNAL ADJUSTMENTS: ____________

USER NOTES PROVIDED ____________

SENSING SURFACE ____________

OVERTRAVEL LIMITS: ____________

SHAFT ALIGNMENT ____________

BACKLASH ______ HOLDING FORCE: ______

STARTING FORCE ______ RUNNING FORCE: ______

ELECTRICAL DESIGN

EXCITATION A-C ___ D-C ___ MAX. ___ NOMINAL ___

VOLTAGE ___ CURRENT ___ FREQUENCY ___

INPUT IMPEDANCE: ___ CURRENT DRAIN: ___

EXTERNAL CONNECTIONS: RECEPTICLE ___

TERMINALS ___ LOADS ___ TYPE ___ FUNCTION ___

INSULATION RESISTANCE ___ BREAKDOWN VOLTAGE ___

IMPEDANCE: OUTPUT ___ ALLOWABLE LOAD ___

OUTPUT NOISE RIPPLE: ____________

SENSITIVITY: EM INTERFERENCE ____________

SHORT CIRCUITING ____________

ENCODER CHARACTERISTICS:

MAX. LOAD VOLT. ___ CURRENT PER DIGIT ___

TYPE OF INTERNAL DRIVE CIRCUIT ____________

TYPE DIODES AND THEIR PURPOSE ____________

STATIC PERFORMANCE

RANGE: UNDIRECTIONAL ___ BIDIRECTIONAL ___

SENSING SHAFT AS REFERENCE POSITION: ______

FULL SCALE OUTPUT/TOLERANCES: ______

LINEARITY (% FSO or % VR): BEST FIT ___ END POINT ___

HYSTERESIS (% FSO or % VR): ______

REPEATABILITY (% FSO or % VR): ______

FRICTION ERROR (% FSO or % VR): ______

RESOLUTION (% FSO or % VR): ______

NULL VOLTAGE (mv/V of excitation): ______

STATIC ERROR BAND (% FSO or % VR): ______

MOUNTING ERROR (% FSO or % VR): ______

ATTITUDE ERROR (% FSO or % VR): ______

DYNAMIC CHARACTERISTICS

MAX. SHAFT SPEED (in./s): ______

SUSTAINED (slowing) SPEED: ______

ENVIRONMENTAL CHARACTERISTICS

AMBIENT TEMP./THERMAL SHOCK: ______

VIBRATION, SHOCK, ACCELERATION LIMIT: ______

ALTITUDE, AMBIENT GASES/CONTAMINANTS: ______

RELIABILITY CHARACTERISTICS

STORAGE/STABILITY LIFE: ______

OPERATING LIFE: ______

the flow rate of a fluid:

* A type where the differential pressure is proportional to flow rate.
* A type where a movable mechanical member is responsive to changes in flow rate.
* A type where a fluid characteristic is sensitive to changes in flow rate.

The above three types of flow sensors will be discussed and illustrated.

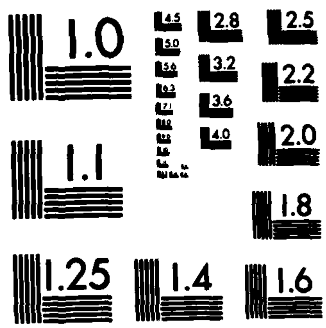
Movable Plunger Flow Sensor -- Fluid flow will move the plunger back against the spring, resulting in a change in the magnetic flux linkage between the primary and secondary coils. A change in output signal amplitude will result from corresponding changes in the flow rate. The greater the flow rate, the greater the plunger displacement against the spring.

Ultrasonic Flow Sensor -- The timing system measures the time required for the ultrasonic energy to traverse the fluid, with and against the flow. The measured times are related to the fluid flow rate.

Ultrasonic Flow Sensor -- The ultrasonic energy reflected from a particle or bubble will be at a frequency shifted from that of the transmitted energy. The shift in frequency corresponds to the flow rate.

AD-A144 208 PARAMETER MEASUREMENT METHODS FOR INTERFACING HYDRAULIC 2/2
SYSTEMS WITH MICR..(U) OKLAHOMA STATE UNIV STILLWATER
FLUID POWER RESEARCH CENTER E C FITCH ET AL. NOV 83
UNCLASSIFIED OSU-FPRC-83-A-51 DAAK70-82-C-0162 F/G 13/7 NL

END



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Temperature Flow Sensor -- The amount of heat transferred to the liquid from the heater is related to the flow rate, given that the power input to the heater is known. The temperature sensor measures the temperature difference of the liquid before and after the fluid flows past the heater. This is related to the heat transferred to the liquid.

Orifice Flow Sensor -- The fluid flowing through the calibrated orifice opening causes a pressure drop to be developed across the orifice. The pressure drop is measured by the pressure transducers and is related to the flow rate.

Venturi Flow Sensor -- The pressure difference developed in the tube is related to the flow rate. The pressure differential is measured by pressure sensors located at the mouth of the tube and one located in the throat.

Pitot Tube Flow Sensor -- Two different pressures are measured with the pitot tube -- static and impact. The static pressure is the hydrostatic pressure of the fluid in the line, and the impact pressure is the pressure caused by the impact of the fluid on the tube plus the static pressure. The static and impact pressures are uniquely related to the flow rate.

Drag Disk Flow Sensor -- The fluid flow causes a force to be exerted on the drag disk which is in turn transmitted to a force sensor through a lever arm. The measured force is related to the flow rate.

Magnetic Flow Sensor -- Fluid flowing through a tube perpendicular to the magnetic field will cause an electric field to be set up mutually perpendicular to both the flow and magnetic field. The strength of the electric field is related to the flow rate.

Gyroscopic Flow Sensor -- The fluid flowing through the spinning tube causes gyroscopic forces to be developed in a direction perpendicular to the tube. This force causes a fixed displacement in the tube related to the flow rate.

Swirl Flow Sensor -- The swirl guide vanes at the opening of the tube cause the fluid to swirl at a uniform frequency. The detector circuitry monitors the frequency of the swirls detected by the probe. The frequency of the swirls is directly related to the flow rate.

Gyroscopic Flow Sensor -- Fluid flow through the tube causes gyroscopic forces to be established. The forces cause the tube to vibrate in a direction perpendicular to the tube plane. This vibration is related to the fluid flow rate.

Turbine Flow Sensor -- Fluid flows through the tube, causing the rotor blades to turn at an angular velocity proportional to the flow rate. The electronic circuitry counts the number of blade passes per unit time to determine the angular velocity and converts this angular velocity to the fluid flow rate.

Flow Sensor Selection Criteria

The most critical factors involved in the selection of flow sensors are the properties of the fluid and the flow rate range to be measured. Of course, the required flow rate accuracy and the pipe configuration into which the flow sensor must fit are also key selection factors.

Specification Sheet

The specification sheet for flow sensors is presented in Table 3.4.

FORCE AND TORQUE SENSORS

Measurand and Associated Terms

Force -- the operative agent which produces an elastic strain in a body and which can cause a change of momentum.

Mass -- the inertial property of a body.

Weight -- the gravitational force of attraction.

Load -- the force applied to a body.

Torque -- the moment of force.

Torsion -- the twisting of an object.

Measurand Units

Absolute (mass) system -- CGS or MKS for metric and FPS for English.

Gravitational (force) system -- Metric and British systems.

Sensing Methods

Force and torque sensors use sensing elements which convert the

Table 3.4. Flow Sensor Specification Sheet.

FLOW SENSOR SPECIFICATION

APPLICATION

SPECIFIC MEASURAND: ____

SENSOR TYPE: ____

SYSTEM I.D.: ____

TRANSDUCTION PREFERENCE: ____

FLUID I.D.: VISCOSITY ____ DENSITY ____ VP ____ ETC. ____

MECHANICAL DESIGN

CASE DIMENSIONS: L ____ W ____ H ____

MOUNTING: ____

IDENTIFICATION: ____

CASE CONSTRUCTION: ____

ELECTRICAL CONNECTIONS. ____

FLUID PORTS: ____

OPERATING RANGES: PRESS. ____ TEMP. ____

PRESSURE DROP: ____ FLOW: ____

PRESSURE: PROOF ____ BURST ____

ACCESS PORTS: ____

OTHER: ____

ELECTRICAL DESIGN

Complete Following, Where Applicable

ELECTRICAL CONNECTORS: ____

IMPEDANCE: INPUT ____ OUTPUT ____

NOMINAL LOAD ____ TOLERANCES ____

EXCITATION VOLTAGE: NOMINAL ____ MAX. ____

EXCITATION CURRENT OR POWER DRAIN: ____

EXCITATION FREQUENCY: ____

OHMIC RESISTANCE (across terminals): ____

OUTPUT NOISE: LEVEL ____ TOLERANCE ____

FREQUENCY OUTPUT: WAVESHAPE ____ DISTORTION ____

INSULATION: RESISTANCE ____ BREAKDOWN VOLT. ____

PERFORMANCE CHARACTERISTICS

FLOW RANGE: LOW ____ HIGH ____ MAX. ____

LINEARITY: BEST FIT ____ END POINT ____

REPEATABILITY (% FSO): ____

SENSITIVITY (% FSO): ____

THRESHOLD (% FSO): ____

CALIBRATION FACTORS: ____

LINE LENGTHS ____ STRAIGHTNESS ____

DYNAMIC: TIME CONSTANT ____

RESPONSE TIME ____ INCREASING FLOW ____

RESPONSE TIME ____ DECREASING FLOW ____

OTHER: ____

ENVIRONMENTAL CHARACTERISTICS

TEMPERATURE ERROR: ____

VIBRATION, SHOCK, ACCELERATION: ____

MOUNTING ATTITUDE: ____

ELECTROMAGNETIC FIELDS: ____

CONTAMINATION: ____

RELIABILITY CHARACTERISTICS

LIFE: STORAGE ____ OPERATING ____

measurand into small mechanical displacements resulting in the deformation of an elastic member -- local strains and gross deflections.

Foil Strain Gauge -- The force applied to the base will cause the foil to be stretched, thus changing the resistance of the device. The amount of strain is proportional to the resistance.

Wire Strain Gauge -- The applied force causes the conductor to increase in length and decrease in diameter. This results in a change in the resistance of the conductor. The change in length and diameter is proportional to the change in resistance.

Bonded Wire Strain Gauge -- The applied force to the base causes the wire to stretch, which results in a change in resistance. The change in resistance is proportional to the change in length of the wire.

Magnetostrictive Force Sensor -- The applied force causes the permeability of the core material to change. This change causes the inductance of the coil to change.

Piezoelectric Force Sensor -- The applied force causes the material to deform, which in turn causes a voltage to be generated.

Semiconductor Force Sensor -- The applied force changes the resistance of the junction between the P-type and the N-type materials.

Transistor Force Sensor -- The applied force alters the electrical characteristics of the sensor materials.

Cantilever Beam Force Sensor -- The applied force causes the cantilever beam to bend, resulting in a deflection at the end of the beam related to the magnitude of the force.

Torsion Force Sensor -- The force applied to the end of the lever arm attached to the cylindrical beam causes the beam to twist through an angle. The angle through which the beam twists is related to the magnitude of the applied force.

Cylinder Force Sensor -- The applied force causes the cylinder to decrease in length an amount proportional to the magnitude of the applied force.

Proving Ring Force Sensor -- The applied force causes the proving ring to deflect an amount related to the magnitude of the applied force.

Sir Diaphragm Force Sensor -- The applied force causes the pressure in the sensor to increase an amount greater than the reference pressure that is related to the magnitude of the applied force.

Phase Difference Torque Sensor -- The amount of torque applied to the rotating shaft causes it to twist through a small angle. This twisting will cause the phase between the two wheels to change. The phase change corresponds to the amount of torque applied.

Sensor Selection Criteria

The primary selection factors for force sensors are generally the range, accuracy characteristics, and the case dimensions. For torque sensors, the key selection factors are range, maximum shaft speed, and accuracy characteristics. Overload characteristics of both force and torque sensors deserve careful consideration. Electrical characteristics of the associated measuring system and the environmental conditions, especially temperature, are particularly important.

Specification Sheet

The specification sheet for force and torque sensors is given in Table 3.5.

LIGHT SENSORS

Measurand and Associated Terms

Light -- electromagnetic radiation whose wavelength is 10^{-2} and 10^{-6} cm (spectrum of visible light is 0.4 to 0.7 micrometres).

Infrared -- radiant energy having wavelengths between 0.76 and 100 micrometres.

Ultraviolet -- radiant energy having wavelengths between 0.4 and 0.001 micrometres.

Measurand Units

Luminance -- candela (cd)

Table 3.5. Force & Torque Sensor Specification.

FORCE & TORQUE SENSOR SPECIFICATIONS

APPLICATION
- SPECIFIC MEASURAND ______
- SENSOR TYPE: ______
- SYSTEM TYPE: ______
- TRANSDUCTION PREFERENCE ______

MECHANICAL DESIGN
- DIMENSIONS: L ______ W ______ H ______
- MOUNTING: ______
- SENSOR CONNECTION: ______
- ELECTRICAL CONNECTIONS ______
- OPTIONAL DEVICES: ______
- NAMEPLATE DETAILS ______
- SENSING MATERIAL ______
- CASE MATERIAL ______
- MISALIGNMENT ______

ELECTRICAL DESIGN
- ELECTRICAL CONNECTORS: ______
- BRIDGE SCHEMATICS: ______
- WINDING CONFIGURATION: ______
- IMPEDANCE: INPUT ______ OUTPUT ______
  - ALLOWABLE LOAD ______
- EXCITATION VOLTAGE: NOMINAL ______ MAX ______
- EXCITATION CURRENT OR POWER DRAIN: ______
- EXCITATION FREQUENCY: ______
- INSULATION RESISTANCE ______
- BREAKDOWN VOLTAGE ______
- SHUNT CALIBRATION ______
  - CHARACTERISTICS ______
  - CONNECTIONS ______

STATIC PERFORMANCE
- RANGE: UNIDIRECTIONAL ______
  - BIDIRECTIONAL ______
- OVERLOAD RATING: SAFE ______ ULTIMATE ______
- OUTPUT TOLERANCES: ______
  - AT EXCITATION ______
- LINEARITY: BEST FIT ______
  - END POINT ______
- HYSTERESIS: ______
- REPEATABILITY ______
- STATIC ERROR BAND: ______
- CREEP OR LIMITING TOLERANCE: ______
- WARM-UP TIME: ______
- SHIFTS: ZERO ______ SENSITIVITY ______
- DEFLECTION FACTOR: ______
- SHAFT SPEED: MAX ______ MIN ______
- MOMENT OF I ______ TORSIONAL STIFF ______
- SHAFT RUNOUT ______ AXIAL END FLOAT ______

DYNAMIC PERFORMANCE
- FREQUENCY: RESPONSE ______ RESONANT ______
- RINGING PERIOD: ______ DAMPING RATIO ______

ENVIRONMENTAL CHARACTERISTICS
- LIMITATIONS: *(temperature, vibration, electromagnetic interference)* ______

RELIABILITY CHARACTERISTICS
- STORAGE/STABILITY LIFE: ______
- OPERATING LIFE: ______

Luminous flux -- lumen (lm)

Illumination -- lux (lx)

Luminosity -- lumens/watt

Sensing Methods

All light sensors are designed to convert electromagnetic radiation into an electrical output.

Photoconductive Light Sensor -- The electrical resistance of the semiconductor material changes with the light intensity. The resistance changes from a very high value with no light to a very small resistance in a bright light.

Photovoltaic Light Sensor -- The output voltage is a function of the illumination on the junction of the two types of semiconductor materials.

Photoemissive Light Sensor -- Electrons are emitted by a cathode when photons of light impinge on it. The anode at a positive potential collects the electrons, causing a current to flow.

Photodiode Light Sensor -- With the diode in the reversed biased condition (applied positive to the N-type and negative to the P-type material), a small amount of leakage current will flow. Light energy will cause the leakage current to increase proportional to its intensity.

Sensor Selection Criteria

The selection criteria for light sensors are sensitivity and spectral response. Other important factors are associated-circuitry characteristics, operating temperature range, and cost.

Specification Sheet

The specification sheet for light sensors is presented in Table 3.6.

LIQUID LEVEL SENSORS

Measurand and Associated Terms

Level -- height above a reference plane.

Level Measurement -- continuous recording and at discrete points.

Measurand Units

Container height -- feet, inches, cm. etc.

Liquid volume -- liters, gallons, etc.

Liquid mass -- kilograms, pounds, etc.

Sensing Methods

Capacitance Liquid Level Sensor -- A change in the liquid level causes a change in capacitance between the probe and the metallic container.

Optical Level Sensor -- The light from the source is reflected by the prism to the detector when the liquid level is below the prism.

Table 3.6. Light Sensor Specification Sheet.

LIGHT SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ______

SENSOR TYPE: ______

SYSTEM TYPE: ______

TRANSDUCTION PREFERENCE: ______

DESIGN CHARACTERISTICS

DIMENSIONS: L ______ W ______ H ______

LENS LOCATION: ______

PINS: TYPE ______ LOCATION ______

DEGREE OF PIN SEALING: ______

CASE MATERIAL: ______

IDENTIFICATION: ______

POLARITY OF LEADS: ______

RESISTANCE: LOAD ______ ELEMENT ______

CAPACITANCE: ______

IMPEDANCE: ______

EXCITATION VOLTAGE: NOMINAL ______ MAX. ______

EXCITATION CURRENT: NOMINAL ______ CATHODE ______

CATHODE TO FIRST DYNODE VOLTAGE: ______

ANODE TO LAST DYNODE VOLTAGE: ______

NUMBER OF DYNODES: ______

SENSING MATERIAL: ______

PERFORMANCE CHARACTERISTICS

OUTPUT: ZERO ILLUMINATION ______

DETECTIVITY: ______

(include definition)

SPECTRAL RESPONSE: ______

PEAK RESPONSE WAVELENGTH: ______

TIME CONSTANTS: NOMINAL ______ MAX ______

RESPONSE TIME: ______ RISE TIME: ______

FIELD OF VIEW: ______

CONVERSION: CURRENT/ILLUMINATION ______

LOAD RESISTANCE EFFECTS: ______

SENSOR RESISTANCE: NOMINAL ______

TOLERANCE ______

OUTPUT vs. ILLUMINATION: Attach Curves

CURRENT GAIN: ______

CATHODE LUMINOUS SENSITIVITY: ______

ANODE SENSITIVITY: ______

CATHODE RADIANT SENSITIVITY: ______

QUANTUM EFFICIENCY: ______

ENVIRONMENTAL CHARACTERISTICS

OPERATING TEMP. RANGE: ______

THERMAL EFFECTS: ______

SHOCK AND VIBRATION: ______

RELIABILITY CHARACTERISTICS

STORAGE/STABILITY LIFE: ______

OPERATING LIFE: ______

When the level is above the prism, the light is no longer reflected to the sensor.

Capacitance Level Sensor -- A change in the liquid level causes a change in the capacitance between the probes.

Pressure Level Sensor -- As the liquid level increases, the hydrostatic pressure increases proportionally at the pressure sensor. The pressure sensor converts the pressure to an electrical signal that corresponds to the liquid level.

Optical Level Sensor -- The light from the source is detected at the optical sensor when the level is below the detector assembly. When the level is between the source and the detector, the light is no longer detected by the detector.

Float Level Sensor -- An increase in the liquid level causes an increase in the float displacement. The displacement is proportional to the level and can be measured by a displacement sensor.

Weight Level Sensor -- A change in the level is directly proportional to a change in the weight of the container. A weight or force sensor converts the weight to an electrical signal corresponding to the liquid level.

Vibrating Paddle Level Sensor -- The vibration of the paddle is damped when it is submersed in the liquid. The position of the paddle determines where the level will be detected.

<u>Temperature Level Sensor</u> -- When the heater and temperature probe are not submerged in liquid, the heat convected away from the heater is less than when submerged. Thus, the temperature probe detects a higher temperature when it is not submerged than when it is submerged.

<u>Conductivity Level Sensor</u> -- If the liquid level increases to the desired set level, the liquid will be in contact with both probes, thus completing the circuit. The two probes act as a switch.

<u>Radiation Level Sensor</u> -- The gamma source produces gamma particles, which are detected and counted at the detector/counter. The count will be less if the level is above the set level than when it is not, thus providing a means of detecting the level of the liquid.

<u>Radiation Level Sensor</u> -- The amount of gamma particles counted by the detector/counter will decrease with an increase in level.

<u>Ultrasonic Level Sensor</u> -- The transmitter/receiver system relates the amount of time required for a sound wave to travel from the ultrasonic sensor to the liquid level and back. This time corresponds to the level of the liquid.

<u>Sensor Selection Criteria</u> -- The first decision that must be made

is whether to have continuous or discrete sensing. After this discussion, primary attention is addressed to the characteristics of the measured liquid, including its temperature, viscosity, and conductivity. Finally, the sensor's dynamic characteristics and accuracy must be compatible with the application conditions.

Specification Sheet

The specification sheet for liquid level sensors is presented in Table 3.7.

PRESSURE SENSORS

Measurand and Associated Terms

Pressure -- a stress exhibited by a fluid.

Absolute Pressure -- a pressure relative to zero pressure.

Gage Pressure -- a pressure relative to ambient pressure.

Differential Pressure -- difference between two pressures.

Static Pressure -- pressure normal to surface along which fluid flows.

Impact Pressure -- pressure resulting from impingement.

Stagnation Pressure -- sum of static and impact pressures.

Vacuum -- a pressure below ambient pressure.

Standard Pressure -- a pressure of one normal atmosphere, 14.7 psia.

Measurand Units

In English Units -- psi, in. water, in. Hg.-- 14.5 psi = 1 bar

Table 3.7. Liquid Level Sensor Specification Sheet.

LIQUID LEVEL SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ______

SENSOR TYPE: ______

SYSTEM TYPE: ______

TRANSDUCTION PREFERENCE: ______

MECHANICAL DESIGN

DIMENSIONS: L ______ W ______ H ______

MOUNTING: ______

SENSING ELEMENT SIZE: ______

ELECTRICAL CONNECTIONS: ______

HYDRAULIC CONNECTIONS: ______

NAMEPLATE DETAILS: ______

CONSTRUCTION MATERIALS. ______

TYPE SEALING: ______

ACCEPTABLE FLUIDS: MEASURED ______ AMBIENT ______

PRESS.: PROOF ______ BURST ______ OPERATING ______

END USE INSTALLATION: ______

FLOW RATE: ______

ELECTRICAL DESIGN

ELECTRICAL CONNECTORS: ______

EXCITATION: CURRENT ___ VOLTAGE ___ FREQUENCY ___

POWER: ______ *CURRENT DRAIN* ______

INSULATION: RESISTANCE ______ BREAKDOWN VOLT. ___

IMPEDANCE: OUTPUT ______ INPUT ______

SIGNAL CONDITIONING: ______

EXCITATION REQUIREMENT: ______

LOAD IMPEDANCE. ______

PERFORMANCE CHARACTERISTICS

MEASURING RANGE: ______

END POINTS ______ SENSITIVITY ______

LINEARITY: BEST FIT ______ END POINT ______

HYSTERESIS: ______

REPEATABILITY: ______

STATIC ERROR BAND: ______

FRICTION ERROR: ______

FLUID CHANGE ERRORS: ______

RESPONSE TIME: ______

TIME CONSTANT: ______

FLOW EFFECTS: VELOCITY ______ TURBULENCE ______

FLUID TEMP.: LOW ______ HIGH ______

OTHER: ______

ENVIRONMENTAL CHARACTERISTICS

TEMP.: OPERATING ______ AMBIENT ______

THERMAL EFFECTS/ACCURACY: ______

VIBRATION, SHOCK, ACCELERATION: ______

ELECTROMAGNETIC EFFECTS: ______

HUMIDITY, SALT WATER EFFECTS: ______

RELIABILITY CHARACTERISTICS

STORAGE/STABILITY LIFE: ______

OPERATING LIFE: ______

In Metric Units -- bar, Kg/cm^2, kilopascal -- 100 bar = 1 kPa

Sensing Method

Practically all pressure sensors sense pressure by means of a mechanical sensing element -- thin-walled elastic members such as plates, shells, or tubes.

Twisted Bourdon Tube Pressure Sensor -- The applied pressure inside the tube causes it to untwist, resulting in an angular displacement. This displacement can be sensed by a displacement sensor.

Helical Bourdon Tube Pressure Sensor -- The applied pressure causes the helical tube to uncoil, resulting in an angular displacement at the opposite end. The angular displacement can be detected and measured by a displacement sensor.

Straight Tube Pressure Sensor -- The applied pressure causes the walls of the tube to stretch and increase in diameter. The diameter variation can be measured by a displacement sensor.

Spiral Bourdon Tube Pressure Sensor -- The applied pressure causes the spiral tube to unwind, resulting in a displacement of the closed end. This displacement can be measured by a displacement sensor and is related to the pressure.

Bellows Pressure Sensor -- The applied pressure causes the bellows to expand lengthwise. The displacement of the closed end can be measured by a displacement sensor and is related to the pressure.

Diaphragm Pressure Sensor -- The applied pressure causes the diaphragm to expand, resulting in a displacement of the diaphragm. This displacement can be measured with a displacement sensor and is related to the pressure.

Circular Bourdon Tube Pressure Sensor -- The applied pressure causes a displacement of the closed end. This displacement can be measured by a displacement sensor and is related to the pressure.

Capsule Pressure Sensor -- The applied pressure causes the capsule to expand, resulting in a displacement. This displacement can be measured by using a displacement sensor, and it is related to the pressure.

Sensor Selection Criteria

The various factors governing the selection of pressure sensors for different applications are their range, accuracy, output, and frequency response. Secondarily, environmental conditions and the nature of the measured fluids are also of importance.

Specification Sheet

The specification sheet for pressure sensors is presented in Table 3.8.

Table 3.8. Pressure Sensor Specification Sheet.

PRESSURE SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ____

SENSOR TYPE: ____

SYSTEM TYPE: ____

TRANSDUCTION PREFERENCE: ____

MECHANICAL DESIGN:

DIMENSIONS: L ____ W ____ H ____

MOUNTING: ____

PRESSURE PORTS: LOCATION ____ TYPE ____

ELECTRICAL CONNECTIONS: LOCATION ____ TYPE ____

FLUID: PRESSURE ____ TYPE ____

CASE SEALING: ____

NAMEPLATE: ____

WEIGHT: ____ DEAD VOLUME: ____

ELECTRICAL DESIGN

ELECTRICAL CONNECTORS: ____

IMPEDANCE: INPUT ____ OUTPUT ____

EXCITATION: NOMINAL ____ LIMITS ____

POWER RATING: ____ WIPER NOISE ____

INSULATION: RESISTANCE ____ BREAKDOWN VOLT. ____

PERFORMANCE CHARACTERISTICS

PRESSURE RANGE: ____

END POINTS: ____ FSO ____

CREEP: ____ RESOLUTION ____

LINEARITY: BEST FIT ____ END POINT ____

HYSTERESIS: ____

REPEATABILITY: ____

FRICTION ERROR: ____

ZERO: BALANCE ____ SHIFT ____

SENSITIVITY SHIFT: ____

WARM-UP PERIOD: ____

REF. PRESSURE: RANGE ____ EFFECTS ____

STATIC ERROR BAND: ____

FREQUENCY RESPONSE: ____

PHASE SHIFT: ____

MIN. RESONANT FREQ. ____ DAMPING RATIO ____

TIME CONSTANT ____ MAX. OVERSHOOT ____

ENVIRONMENTAL CHARACTERISTICS

TEMP.: OPERATING ____ AMBIENT ____

THERMAL ERROR BAND: ____

THERMAL: ZERO SHIFT ____ SENSITIVITY SHIFT ____

ERROR: ACCELERATION ____ VIBRATION ____

EFFECT OF SHOCK, HUMIDITY, & SALT FOG: ____

EFFECT OF MAGNETIC FIELDS: ____

RELIABILITY CHARACTERISTICS

PRESS. RATING: BURST ____ PROOF ____

STORAGE/STABILITY LIFE: ____

OPERATING LIFE: ____

SOUND-PRESSURE SENSORS

Measurand and Associated Terms

Sound -- an oscillation in an elastic or viscous medium.

Sound Energy -- total energy minus the energy which would exist with no sound waves present.

Sound Pressure -- the total instantaneous pressure at a given point, in the presence of a sound wave, minus the static pressure at that point.

Sound Level -- the weight sound-pressure level obtained with a standard sound level meter.

Sound Intensity -- the average rate of sound energy transmitted in a specified direction through a unit area normal to this direction at a given point.

Sound-Pressure Sensor -- a device which provides a usable (electrical) output in response to sound pressure which is to be measured.

Measurand Units

Sound Pressure -- in terms of sound pressure level in decibels (db).

Sensing Methods

The flat diaphragm is the universal sensing element for practically all sound-pressure sensors.

Carbon Sound Sensor -- The sound waves are collected in the cone and cause the diaphragm to vibrate. The vibrating diaphragm produces a force on the carbon granules which changes the resistance of the carbon. The change in resistance of the carbon corresponds to the intensity of the sound waves.

Capacitance Sound Sensor -- The sound waves cause the diaphragm to move up and down. This motion causes the capacitance to change between the diaphragm and the fixed metal plate. The varying capacitance corresponds to the intensity of the sound waves.

Piezoelectric Sound Sensor -- The sound waves cause the diaphragm to move, resulting in a force being applied to the piezoelectric crystal. The varying force applied to the crystal causes a varying voltage to be generated proportional to the intensity of the sound waves.

Inductance Sound Sensor -- The sound waves collected by the cone of the sensor cause the diaphragm to move, resulting in the motion of the plunger inside the wire coil. This motion of the plunger causes the inductance of the coil to vary corresponding to the intensity of the sound waves.

Electromagnetic Sound Sensor -- The sound waves collected by the cone cause the diaphragm to move, resulting in the motion of the movable coil in the magnetic field set up by the permanent magnet. This motion causes a voltage to be generated across the coil corresponding to the intensity of the sound waves.

Sensor Selection Criteria

The limited number of sensor designs available on the market makes the selection task much less laborious than for most other measurands. Frequency response and frequency range limits are the two primary selection factors.

Specification Sheet

The specification sheet for sound-pressure sensors is presented in Table 3.9.

SPEED AND VELOCITY SENSORS

Measurand and Associated Terms

Speed -- the magnitude of time rate of change of displacement.

Velocity -- the time rate of change of displacement with respect to a reference point.

Average Speed -- the magnitude of the average velocity vector.

Average Velocity -- the total displacement divided by the total movement time.

Instantaneous Velocity -- the first derivative of the displacement.

Measurand Units

Linear -- length per unit time, such as in. per sec. or cm per sec.

Angular -- radians or revolutions per unit time, such as rad/sec and rpm.

Table 3.9. Sound Sensor Specification Sheet.

SOUND SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ____

SENSOR TYPE: ____

SYSTEM TYPE: ____

TRANSDUCER PREFERENCE: ____

MECHANICAL DESIGN

CASE DIMENSIONS: L ____ W ____ H ____

MOUNTING: ____

IDENTIFICATION: ____

CASE CONSTRUCTION: ____

SENSOR WEIGHT: ____

TRANSDUCTION ELEMENT: ____

SENSING ELEMENT: ____

CASE SEALING: ____

LIMITS ON ATM. CONTAMINANTS: ____

ENCLOSED OR SEMI–ENCLOSED VOL.: ____

RATED MOUNTING FORCE: ____

CONNECTING CABLE *(details)*: ____

ELECTRICAL DESIGN

ELECTRICAL CONNECTOR: ____

EXCITATION: VOLTAGE ____ CURRENT ____

FREQUENCY ____ POWER ____

EQUIPMENT: SIGNAL CONDITIONING ____

EXCITATION ____

INSTALLATION: RESISTANCE ____

OUTPUT: IMPEDANCE ____ NOISE ____

TRIBOELECTRIC CABLE NOISE: ____

INTERNAL GROUNDING: ____

LOAD IMPEDANCE: ____

PERFORMANCE CHARACTERISTICS

RANGE: ____ OUTPUT ____

SENSITIVITY: ____ LINEARITY ____

FREQUENCY RESPONSE: ____

OVERLOAD: ____ DIRECTIVITY ____

THRESHOLD: ____ THERMAL EFFECTS ____

AMBIENT PRESSURE ERROR: ____

ATMOSPHERIC EFFECTS: ____

VIBRATION ERROR: ____

ENVIRONMENTAL EFFECTS

ON FREQUENCY: ____

AMBIENT TEMPERATURE: ____

RELIABILITY CHARACTERISTICS

STORAGE/STABILITY LIFE: ____

OPERATING LIFE: ____

Sensing Methods

The transduction element used in velocity sensors is almost invariably of the electromagnetic type, in which a change of magnetic flux induces an electromotive force in a conductor.

Electromagnetic Velocity Sensor -- The coil moving through the magnetic field set up by the two magnets causes a voltage to be developed across the coil. This voltage is proportional to the velocity.

Electromagnetic Angular Velocity Sensor -- The armature with a wire coil wound on it is rotated in a magnetic field set up by the permanent magnets, which causes a voltage to be induced across the coil winding. The voltage generated is proportional to the angular velocity.

Hall Effect Velocity Sensor -- The velocity of the magnet with respect to the Hall element is related to the generated Hall voltage.

Optical Disk Angular Velocity Sensor -- The angular velocity at which the disk rotates determines the number of pulses produced by the photoconductor sensor per unit time. The counter circuitry converts the number of pulses per unit time to an angular velocity.

Electromagnetic AC Angular Velocity Sensor -- The rotating magnet induces an AC voltage in the stationary coil. The frequency of the AC voltage is proportional to the angular velocity.

Sensor Selection Criteria

Linear velocity sensors are generally selected on the basis of the frequency response, operating temperature range, sensitivity, weight, and mounting position. The selection of angular-speed sensors is primarily based on the type of readout or signal-condition equipment needed, on range, accuracy characteristics, cost, sensitivity and output characteristics, number of separate outputs needed, excitation requirements, type of installation, weight, and environmental limitations.

Specification Sheet

The specification sheet for speed and velocity sensors is presented in Table 3.10.

STRAIN SENSORS

Measurand and Associated Terms

Strain -- the deformation of a solid resulting from a stress.

Stress -- the force acting on a unit area of a solid.

Modulus of Elasticity -- the ratio of stress to the corresponding strain.

Poisson's Ratio -- the ratio of transverse to longitudinal unit strain.

Strain Measure -- ratio of the dimensional change to total value of undeformed dimension.

Strain Gage -- generally a resistive strain sensor.

Table 3.10. Speed & Velocity Sensor Specifications.

SPEED & VELOCITY SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ____________

SENSOR TYPE: ____________

SYSTEM TYPE: ____________

TRANSDUCER PREFERENCE: ____________

MECHANICAL DESIGN

CASE DIMENSIONS: L ______ W ______ H ______

MATERIAL/FINISH: ____________

MOUNTING: ____________

ELECTRICAL CONNECTOR: ____________

IDENTIFICATION: ____________

SENSOR WEIGHT: ____________

SENSOR SHAFT: MATERIAL ____________

DIMENSION ______ COUPLING ______

MATERIALS: BRUSHES ______ COMMUTATORS ______

TACHOMETER BEARINGS: ____________

FAIL-SAFE PROVISIONS: ____________

ELECTRICAL DESIGN

INSULATION: RESIST. ______ BREAKDOWN VOLT. ______

RECEPTACLE PIN I.D.: ____________

IMPEDANCE: LOAD ______ OUTPUT ______

OUTPUT: FREQUENCY ______ RESISTANCE ______

EXCITATION: VOLTAGE ______ POWER ______

PERFORMANCE CHARACTERISTICS

RANGE: ______ SENSITIVITY/FSO ______

HYSTERESIS ______ REPEATABILITY ______

LINEARITY: ______ FREQ. RESPONSE ______

TRANSVERSE SENSITIVITY: ____________

DAMPED NATURAL FREQ.: ____________

TORQUE: STARTING ______ RUNNING ______

MOMENT OF INERTIA: ____________

OUTPUT NOISE: ____________

OUTPUT AMPLITUDE: ____________

ALLOWABLE VARIATION: ____________

UNIFORMITY OF AMPLITUDE: ____________

ADJUSTABLE AMPLITUDE RANGE: ____________

OUTPUT FREQUENCY: ____________

PULSE CHARACTERISTICS: ____________

ALLOWABLE HARMONIC CONTENT: ____________

ENVIRONMENTAL CHARACTERISTICS

LIMITATIONS ON OPERATIONS DUE TO: ____________

TEMP. ______ SHOCK ______ VIBRATION ______

ACCELERATION ____________

ELECTROMAGNETIC FIELD ____________

HIGH SOUND PRESSURE ____________

MAGNETIC FIELDS ____________

NUCLEAR RADIATION ______ HUMIDITY ______

AMBIENT PRESSURE ____________

ATMOSPHERIC CONTAMINANTS ____________

RELIABILITY CHARACTERISTICS

LIFE: STORAGE ____________

STABILITY ______ OPERATING ______

Measurand Units

Strain -- in micro-inches per inch, percent for large deformations and in microstrain for medium and small deformations. One microstrain is the ratio of 10^{-6} of a length unit to this length unit.

Stress -- force per unit of area; e.g., lb/in^2, kg/cm^2, etc.

Sensing Method

The device used for the vast majority of strain measurements is the resistive strain sensor or strain gage. It consists of a conductor or semiconductor of small cross-sectional area which is mounted on the measured surface so that it elongates or contracts with that surface. Deformation of the sensing material causes it to undergo a change in resistance. Hence, a strain gage senses strain by its own deformation and converts the deformation into a resistance change. Since strain gages are used extensively as force sensors, they were covered under the section on force sensors.

Specification Sheet

The specification sheet for strain sensors is presented in Table 3.11.

TEMPERATURE SENSORS

Measurand and Associated Terms

Temperature -- the thermal state of a body and its power to heat other bodies, a measure of mean kinetic energy of the molecules of a substance -- the potential of heat flow.

Table 3.11. Strain Sensor Specification Sheet.

STRAIN SENSOR SPECIFICATIONS

APPLICATION

SPECIFIC MEASURAND: ______

SENSOR TYPE: ______

SYSTEM TYPE: ______

TRANSDUCTION PREFERENCE: ______

MECHANICAL DESIGN

GAGE DIMENSIONS: L ______ W ______

GRID LENGTH: ______ TERMINALS ______

LEADS: THICKNESS ______ MATERIAL ______

INSULATION ______ LENGTH ______

SPACING ______

FOR BONDED GAGE: BASE LENGTH ______

WIDTH ______ THICKNESS ______ MATERIAL ______

FOR SURFACE–TRANSFERABLE GAGE:

STRIPPABLE CARRIER: SIZE ______ MATERIAL ______

GRID: MATERIAL ______ DIAMETER ______

FOIL THICKNESS ______

RECOMMENDED BONDING METHODS:

CEMENT ______ CURE TIME ______ TEMP. ______

PRESSURE ______ INSULATION RESISTANCE ______

RESISTANCE: HUMICITY ______ MOISTURE ______

ELECTRICAL CHARACTERISTICS

GAGE RESISTANCE: ______ TOLERANCES ______

POWER RATING: ______

MAX. EXCITATION CURRENT: ______

GAGE FACTOR: NOMINAL VALVE ______ TOLERANCES ______

STRAIN RANGE:

LINEARITY (independent): ______

HYSTERESIS: ______ CREEP ______

DRIFT: ______

LIFE REQUIREMENTS (cycling): ______

ENVIRONMENTAL CHARACTERISTICS

PERFORMANCE TOLERANCE FOR TEMP.: ______

NUCLEAR RADIATION EFFECTS: ______

ILLUMINATION EFFECTS: ______

MAGNETIC FIELDS: ______

ATMOSPHERIC CONDITIONS: ______

ALLOWABLE OVERLOAD: ______

RELIABILITY CHARACTERISTICS

STORAGE LIFE: ______

STABILITY LIFE: ______

FATIGUE LIFE: ______

Heat -- energy in transfer due to temperature differences.

Heat Transfer -- thermal energy in transition by:

Conduction -- diffusion

Convection -- fluid movement

Radiation -- electromagnetic waves

Measurand Units

Temperature -- in degrees Celsius or Fahrenheit and degrees Kelvin or Rankine, depending on the temperature scale used.

Heat Flux -- BTU/ft^2/hr, Watts/cm^2 or Calories/cm^2/s

Sensing Methods

All temperature sensors are either of the thermoelectric or resistive type. These types are presented below:

Radiation Pyrometer -- Radiation pyrometers (also called radiation thermometers) measure thermal radiation and provide an output in terms of temperature or one which is convertible to temperature.

Radiation Pyrometer -- The temperature in this case is inferred from the total heat energy which is caused to impinge on a thermocouple.

Thermocouple -- When a temperature difference exists between the thermocouple junction and the reference end of the two materials, a voltage is generated proportional to the temperature of the junction.

Optical Pyrometer -- The viewer compares the brightness of the hot object and the reference filament. If the filament is too hot, it will appear as a bright spot on the hot object. If the filament is too cold, it will appear as a dark spot on the hot object. When the filament is at the same temperature as the hot object, it will be at the same brightness and therefore appears invisible to the viewer. By adjusting the current through the filament, the brightness (temperature) is adjusted.

Resistive Thermometry -- An electrical resistive material can be a conductor or a semiconductor. A change in the resistance of the material is proportional to the change in the temperature.

Sensor Selection Criteria

In selecting a temperature sensor, a limited number of factors are of paramount importance: the nature and characteristics of the measured fluid or solid, the measuring range, the time constant, and the type of associated signal conditioning circuitry and readout equipment available.

Specification Sheet

The specification sheet for temperature sensors is presented in Table 3.12. The specification sheets for selecting signal amplifiers, filters and monitors are shown in Tables 3.13, 3.14, and 3.15, respectively.

Table 3.12. Temperature Sensor Specification Sheet.

TEMPERATURE SENSOR SPECIFICATIONS

APPLICATION

- SPECIFIC MEASURAND: ____
- SENSOR TYPE: ____
- SYSTEM TYPE: ____
- TRANSDUCTION PREFERENCE: ____

MECHANICAL DESIGN

- DIMENSIONS: L ____ W ____ H ____
- MOUNTING: ____
- STEM LENGTH: ____ STAGNATION FITTING: ____
- WEIGHT: ALLOWABLE ____ ACTUAL ____
- MEASURED FLUIDS: ____
- PRESSURE: PROOF ____ OPERATING ____ BURST ____
- LEAKAGE: ALLOWABLE ____
- LEAD PULL-OUT STRENGTH: ____
- SENSOR ELEMENT: TYPE ____
  - MATERIAL TYPE ____
- IDENTIFICATION: ____
- ELECTRICAL CONNECTIONS: ____

ELECTRICAL DESIGN CHARACTERISTICS

- GROUNDING REQUIREMENTS: ____
- ISA SCHEMATIC DIAGRAMS: ____
- INSULATION: RESISTANCE ____ B.D. VOLTAGE ____
- EXCITATION: CURRENT ____ VOLTAGE ____
  - POWER ____ RESISTANCE ____

PERFORMANCE CHARACTERISTICS

- RANGE: ____
- TEMPERATURE: MAX ____ MIN ____
- OUTPUT: NOMINAL FSO ____
- REPEATABILITY: ____
- STABILITY: ____
- CALIBRATION INTERCHANGEABILITY: ____
- THERMOELECTRIC POTENTIALS: ____
- SELF-HEATING (I^2R heating): ____
- CONDUCTION ERROR ____
- MOUNTING ERROR: ____
- ERROR BAND: ____
- TIME CONSTANT: ____
- RESPONSE TIME: ____
- RECOVERY ERROR: ____

ENVIRONMENTAL CHARACTERISTICS

- VIBRATION EFFECTS: ____
- ACCELERATION EFFECTS: ____
- POST-SHOCK: ____

RELIABILITY CHARACTERISTICS

- STORAGE TEMP./LIFE: ____
- THERMAL SHOCK: ____
- HUMIDITY: ____
- CONTAMINANTS: ____

Table 3.13. Signal Amplifier Specification Sheet.

AMPLIFIER SPECIFICATIONS

SHEET 1 OF 2

MANUFACTURER

MODEL NUMBER ____________

OTHER INFO. ____________

TYPE OF AMPLIFIER ____________

ELECTRICAL DESIGN

INPUT OFFSET VOLTAGE ± ____________ mv max (25 C)

VS. TEMPERATURE ± ____________ μV/C

VS. SUPPLY VOLTAGE ____________ μV/V

VS. TIME ____________ μV/month

INPUT BIAS CURRENT ____________ pA max (26 C)

VS. TEMPERATURE ____________ nA/C

VS. SUPPLY VOLTAGE ____________ nA/V

OPEN LOOP GAIN

FULL LOAD ____________ dB

NO LOAD ____________ dB

FREQUENCY RESPONSE

UNITY GAIN ____________ Hz

SLEW RATE ____________ V/μsec.

RATED PUTPUT

VOLTAGE ± ____________ V min.

CURRENT ± ____________ mA min.

OUTPUT RESISTANCE ____________ Ω

SHORT CIRCUIT CURRENT ____________ mA

CAPACITIVE LOAD RANGE ____________ pF

DYNAMIC RESPONSE

GAIN-BANDWIDTH PRODUCT ____________ MHz

FULL POWER BANDWIDTH ____________ KHz

SETTLING TIME (0.1%) ____________ μsec

RISE TIME (10%, 90%) ____________ nsec

SMALL SIGNAL OVERSHOOT ____________ %

PHASE MARGIN ____________ deg

OVERLOAD RECOVERY ____________ μsec.

DIGITAL INPUT (esp. for instrumentation amplifier)

INPUT "LOW" THRESHOLD ____________ V

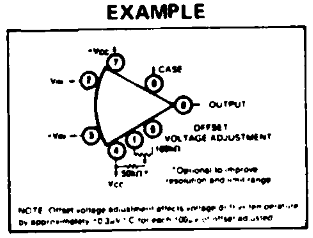
INPUT "HIGH" THRESHOLD ____________ V

MAX. CLOCK FREQUENCY ____________ MHz

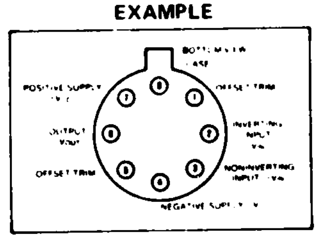
SETUP TIME ____________ nsec.

HOLD TIME ____________ nsec.

CONNECTION DIAGRAM EXAMPLE



PIN CONFIGURATION EXAMPLE



AMPLIFIER SPECIFICATIONS

SHEET 2 OF 2

TYPICAL PERFORMANCE CURVES

FREQUENCY RESPONSE (GAIN (dB) VS. FREQUENCY)

VOLTAGE NOISE VS. FREQUENCY

VOLTAGE NOISE SPECTRUM

INPUT WIDEBAND VOLTAGE NOISE VS. BANDWIDTH

TOTAL NOISE VS. SOURCE RESISTANCE

VOLTAGE NOISE VS. TEMPERATURE

VOLTAGE NOISE VS. SUPPLY VOLTAGE

CURRENT NOISE VS. FREQUENCY

SUPPLY CURRENT VS. SUPPLY VOLTAGE

OFFSET VOLTAGE DRIFT OF REPRESENTATIVE UNITS

LONG TERM DRIFT OF REPRESENTATIVE UNITS

WARM UP DRIFT

OFFSET VOLTAGE CHANGE DUE TO THERMAL SHOCK
(absolute change in input offset voltage vs. time)

INPUT BIAS CURRENT VS. TEMPERATURE

INPUT OFFSET CURRENT VS. TEMPERATURE

OPEN - LOOP GAIN VS. FREQUENCY

SLEW RATE VS. TEMPERATURE

GAIN BANDWIDTH PRODUCT VS. TEMPERATURE

PHASE MARGIN VS. TEMPERATURE

OPEN - LOOP VOLTAGE GAIN VS. SUPPLY VOLTAGE

MAXIMUM UNDISTORTED OUTPUT VS. FREQUENCY

MAXIMUM OUTPUT SWING VS. RESISTIVE LOAD

Table 3.14. Signal Filter Specification Sheet.

FILTER SPECIFICATIONS

APPLICATION ______

CUT-OFF FREQUENCY ______

IMPEDANCE INPUT ______

OUTPUT ______

* SPECIFICATION OF AMPLIFIER IN ACTIVE FILTER CIRCUITRY REFER TO AMPLIFIER SPECIFICATION.

Table 3.15. Microcomputer & Monitor Specification Sheet.

MICROCOMPUTER & MONITOR SPECIFICATIONS

CPU AND MEMORY
- CPU ______
- RAM ______
- ROM ______

BUILT-IN PERIPHERALS
- DISPLAY ______
- PRINTER ______
- CLOCK ______
- TONE GENERATOR ______
- OTHERS ______

COMMUNICATIONS
- RS 232C ______
- SERIAL ______
- OTHERS ______

PERIPHERAL INTERFACES
- BARCODE READER ______
- CASSETTE ______
- SYSTEM BUS ______

CONNECTOR CONFIGURATION
- ______
- DISK DRIVE ______
- ______
- ______
- I/O PORT ______
- ______
- ______

SWITCHES, INTERNAL
- ______

SWITCHES, EXTERNAL
- MAIN POWER ______
- RESET ______
- OTHERS ______

KEYBOARD AND CHARACTER SET
- TYPE ______
- FUNCTION ______
- TOTAL NO OF KEYS ______
- FUNCTION KEYS ______
- SPECIAL KEYS ______
- TEN KEY PAD ______
- GRAPHIC SHIFT ______
- INTERNATIONAL CHARACTER SET ______

ENVIRONMENTAL
- TEMPERATURE ______
  - OPERATING ______
  - CHARGE ______
  - DATA INTEGRITY ______
  - DATA STORAGE ______
- HUMIDITY ______

MECHANICAL DESIGN
- SIZE ______
- WEIGHT ______

OPTIONS ______

CHAPTER IV

DISCUSSION AND FURTHER RECOMMENDATIONS

DISCUSSION

Progress in engineering has historically been achieved by accepting failures in service and counteracting with improvements in materials, design principles and protection methodology. Today, a system designer is expected to have more than a hazy notion as to the service life and reliability of his system and its associated components. Under these circumstances, the prevention of failures can be effectively practiced and is far better than applying the "let fail then repair" or breakdown maintenance philosophy. With these thoughts in mind, it is obvious that the stage has been set for the use of condition monitoring concepts in hydraulic systems, the detection of incipient failures, and the application of the prognostic approach to failure prevention -- timely maintenance and on-site improvements in material and design.

This research initiated the study of the parameter measurement methods for interfacing hydraulic systems with microelectronic instruments and controllers. The overall objective of this research survey of technical data and development of a specification format for measuring devices has been successfully met through the effort of this study. The results provide valuable technical knowledge in the evaluation and selection of parameter measurement devices for a hydraulic control system.

Condition monitoring is accomplished by selecting suitable parameters for assessing the abnormality or degree of deterioration and reporting their values at designated intervals of time or on a continuous basis. Needless to say, a good understanding of measuring device properties can aid one in monitoring system performance. In the past, condition monitoring relied heavily upon the sensory perceptions of the operator. However, as the structure and function of hydraulic systems become more complicated, and the efficiency and accuracy of signal response are of concern, response of human beings can no longer satisfy the monitoring and control requirements. More efficient and accurate sensing devices are deemed necessary.

Recently, the use of microprocessor-based monitoring and operational control systems has become widespread in the automobile industry. For instance, fuel system controllers monitor numerous parameters, both internal and external to the engine, and adjust idle speed, carburation, etc., for optimum performance through computer manipulation of the data. This new trend has strongly signified the importance of this study -- an investigation of sensing techniques for interfacing hydraulic systems with microelectronic instruments and controllers. It is believed that microcomputer-based design will replace more traditional mechanical and hydraulic designs in process in the near future. Obviously, the development of condition monitoring and operational control systems which are compatible with modern machine design is unavoidable.

As was mentioned earlier, sensors and microprocessors play an important role in detecting system parameters. It should be noted that the sensor can only translate a physical effect into an electrical signal, and the signal is processed by interfacing units into a format that is acceptable to the microprocessor. At this point, the microprocessor cannot provide us any meaningful information without the aid of a pre-established algorithm used to "judge" system performance degradation. In other words, to make a microprocessor "smarter" requires a rationale which is able to identify both incipient and impending failure modes and eventually make recommendations for remedial and failure preventive action.

A comprehensive survey on signal detectors, conditioners, and processors which are commercially available has been made during the past year. The results indicate that, as far as the hydraulic control system is concerned, there are a sufficient amount of devices available for detecting primary parameters; for example, force, pressure, flow rate, temperature, etc. Nevertheless, almost none of these devices can be used simply to monitor system condition and for the control process. The reason for this drawback is mainly due to the lack of both the knowledge in assessing system performance and techniques for microcomputer control applications. In order to extend the results obtained in this study to practical applications, either condition monitoring or process control, it is vital that rigorous rationales in assessing performance degradation and the study of microcomputer control be developed. Fortunately, based on the experience gained in conducting related contract work not only for the U.S. Army during the past 14 years but also for over 100 member companies of the BFPR and FRH programs at the FPRC, the FPRC/OSU is in excellent position to successfully execute the condition monitoring and process control programs.

There are many rationales for assessing hydraulic components/systems performance degradation which have been developed or are being developed at the FPRC which have been widely recognized and accepted by national and international standards organizations. To promote the results of this research and rationales developed at the FPRC to complete the study of condition monitoring, it is recommended that the following events should be comprehensively studied and the existing rationales modified into a format which is suitable for implementation on microcomputer-based instruments.

FURTHER RECOMMENDATIONS

The recommended events include the study and modification of system performance assessment rationale, a microcomputer control algorithm, and a machine health monitoring system. The principle and prospective applications for each individual event are illustrated in the following sections.

System Performance Assessment Rationale

Conditioning monitoring is concerned with extracting information from a system or machine to indicate its condition while still in operation and to enable predictive maintenance to be carried out with safety and economy before the break-down point is reached. In practice, it is desired that the outputs of the condition monitoring system be extremely simple or be in the form of warnings and instructions regarding both incipient and impending failures. Such outputs may be made on the basis of interpretations, inferences, and fault indicators generated by the computational elements of the monitoring system. Considering the simplicity of signal manipulation, a "severity index" assigned to the performance concerned to indicate degradation in performance is preferred. With this in mind, a series of severity indices have been developed at the FPRC. For example, in the aspect of contamination control, four "primitive" indices (namely Beta, Gamma, Omega, and Zeta) have been developed to indicate the severity of filter performance, working fluid properties, component material characteristics, and the entrained abrasive particle property, respectively.

It is well known that component wear can be reduced through two approaches: either by filtration or by a tribological process. A filter is used to remove harmful abrasive particles from systems; that reduces the probability of components being attacked. On the other hand, components also can be protected by increasing fluid film thickness between precision surfaces or increasing fluid lubricity. Therefore, if adequate instruments (for example, a particle counter, viscometer, ferrograph) are used to obtain "primary" parameters (particle concentration, fluid viscosity, temperature, etc.), and then to process these measurands according to the developed Beta, Gamma, Omega and Zeta principles in a microcomputer, the variation of these "indices" will immediately indicate the cause of performance degradation; and, furthermore, the residual service life of components can be obtained.

Efficiency degradation has been recognized as the major index in assessing transmission system performance and system energy productivity. This rationale has been successfully implemented on the efficiency analyzer at the FPRC. The efficiency analyzer is able to analyze over-all system efficiency degradation. In addition, according to the trace of the pressure-flow or force-velocity points with respect to time shown on the monitoring display, the analyzer is able to provide the degree of degradation with regard to volumetric loss or mechanical loss.

Another example of a performance analyzer is the Statistical Analog Monitoring System (STAM), which utilizes a fully operational microcomputer to do parameter level analysis, duty cycle severity analysis and strain cycle severity analysis. Instead of using the conventional time-based system, the STAM uses the magnitude of the parameter (level of intensity). Thus, a given operating parameter is historicized by reducing a time-varying function into a set of statistics for describing the parameter's behavior. Its achievement assures success in the development of the on-board condition monitoring system.

Microcomputer Control Algorithm

It is significant to understand the function of a microcomputer in a control system before the rationales of failure and process control are implemented on the microcomputer. Over the past ten years, the FPRC has spent a lot of effort on the study of microcomputer control. Recently, a general purpose hydraulic system test robot has been under development. This robot utilizes a new technique which marries the principles of microcomputer control and electrohydraulic control together to execute the desired work function. Because of its success in the design of a control function, the technique used in the development of the FPRC robot can be simply transferred to the development of a "smart" machine health monitoring system. In order to clarify the crux of the microcomputer control algorithm, the control function of the FPRC robot will be illustrated as an example to explain this conceptual approach to microcomputer control. In practice, a microcomputer is used to perform data processing, data manipulation and interpretation, and operational control.

After the electric signal from the sensors has been received by the microcomputer, the data can be processed either through the high level language or machine language. In some cases, it may also be processed by both languages. Selection of a processing language is very dependent on the function to be executed. Frequently, it is preferred to use a high level language (for example, BASIC, PASCAL, FORTRAN, etc.) to process computer algorithms or to interact with human operators. On the other hand, machine language is used to process simple algorithms or to interface with signals.

The FPRC robot control system utilizes both languages to process data. It uses machine language for fast execution, while it uses the

BASIC language to communicate with human operators. This approach has been proven to be better and more efficient than a single language approach.

Data manipulation and interpretation are accomplished by comparing the pre-established rationales in the microcomputer system. The comparison results therefore set the direction for the next action, either to display system messages on the monitor or to perform process control. If process control is requested, a control signal will be generated. In the case of a continuous feedback system, the signal is continuously generated, which forms a feedback loop between the microcomputer and the system to be controlled. On the other hand, the human operator is involved in a discrete control system to link the microcomputer and control system together. For example, the FPRC robot control system monitors the motion of the robot through the sensors and microcomputer system. The position of the robot can be clearly displayed on the terminal. Information (e.g., the coordinate) of the motion trace will be analyzed by a pre-established algorithm to determine the next task. Furthermore, at some critical position, the microcomputer will "tell" the robot to stop and then wait for the "command" set by the human operator. Consequently, the performance of the robot can be monitored; meanwhile, the results obtained can be directly applied to control the system. The FPRC robot control system configurates a very important aspect -- it adapts existing equipment and concepts for on-board use. This approach, coincidentally, meets the design philosophy of the FPRC condition monitoring plan. More significantly, success in the robot control system design implies a high credibility and gives confidence to extend this research to the development of the condition monitoring system at the FPRC.

Machine Health Monitoring System

Based on the results of this research and the recommendations made above, a condition monitoring system should be implemented to recognize and perform the following information:

1. Specification of system requirements.
   a. Operation
   b. Control
   c. Performance
   d. Safety
2. Primary system information.
   a. Limitations
   b. Ratings
   c. Failure modes
   d. Maintenance programs
3. Secondary system information.
   a. Actual conditions
   b. Transient effects
   c. Duty cycles
   d. Load cycles
   e. System response
   f. Parametric changes
   g. Records, charts

4. Interpretation.
    a. Parameter correlation
    b. Actual system efficiency
    c. Performance data acquisition
    d. Data bank inputs
    e. Failure causes
5. Decisions.
    a. System condition status
    b. Failure location
    c. Failure diagnosis
    d. System maintenance status
6. Execution.
    a. Satisfy system requirements
    b. Satisfy maintenance program
    c. Satisfy system integrity

Obviously, these requirements can be efficiently achieved by using the distributed intelligence approach used in the FPRC robot system. This approach utilizes the on-chip microcomputer; namely, each hydraulic component has its own intelligence. It operates independent of the other components of the system. However, these chips are governed by a host computer. The entire control system includes four distinct modes: monitoring, regulation, emergency, and cooperative modes.

In the monitoring mode, the sensor detects system condition. It responds to a critical condition by sending a signal to the main computer immediately; otherwise, it sends the signal periodically.

The function of the regulation mode is to operate the process control according to the sensed results.

The emergency mode is designed to notify the main computer of the occurrence of any abnormal conditions and then get into an emergency remedy program. A warning or failure signal should be displayed.

If any on-chip microcomputer fails, the main computer will call the cooperative mode to enable another on-chip microcomputer to share and take care of the operation until the failed one is repaired. This implementation highly increases the reliability of the condition monitoring system.

From the foregoing discussions, it is realized that condition monitoring for hydraulic systems is an indispensable step towards the assessment of system performance reliability. The FPRC has an extensive background in hydraulic systems, which gives an experienced position in engineering appraisal of condition monitoring. The FPRC has been conscious of the necessity for more reliable hydraulic systems. The well-known failure theories developed and proved at the FPRC are steps already overcome to the implementation of hydraulic systems with condition monitoring. It is essential to understand component performance and systems in general in order to assess the condition monitoring system in the most efficient way and to develop a reliability approach which accurately represents system performance.

CHAPTER V

CONCLUSIONS

From the research investigation described in the preceding chapters, several noteworthy conclusions can be made. The major accomplishments and conclusions of this research are listed as follows:

1. The results of the comprehensive survey made on the parameter measurement methods for hydraulic control systems showed that the greatest concern in using microcomputers on fluid power systems is not related to the computer itself but rather to finding suitable sensors and actuator controllers.
2. In any parameter measurement system, there are three major elements -- detector, signal modifier, and process unit. A detector (or sensor) is an element used by an instrument transducer to sense the desired quantity. The signal modifier and process unit are employed to manipulate received signals.
3. A sensor can normally be identified by any of the following technical methods: measurand, transduction principle, passivity, construction features, and effective range.
4. The operating principle of sensors which interface with microelectric instruments and controllers is governed by some basic electrical properties: capacitance, resistance, inductance, or a combination of these.
5. Sensors generally require some type of circuitry or equipment in order to function and display the magnitude of the measurand. Therefore, knowledge of the interface between a sensor and a

signal conditioning and process unit cannot be avoided.

6. In practice, a sensor-computer interfacing circuit normally includes an amplifier circuit to scale the signal, a filter circuit to eliminate any noise in the analog signal that may cause an error, a microprocessor to control program sequence, and a monitor to display the desired system information.

7. The performance characteristics of parameter measurement devices are critical to their application. These characteristics include measurand, electrical, static, and dynamic. The measurand characteristics are concerned with the response of the sensor to only a specific measurand. The electrical characteristic highlights the significance of impedance matching. Static performance characteristics concern accuracy-related terms of the sensor, while dynamic performance characteristics describe the ability of a parameter measurement device to follow a rapidly varying measurand.

8. After comprehensive study of the specification of most commercially available sensors, twelve specification sheets have been developed for assisting in the selection and procurement of sensors. They are presented in a uniform format with measurand and associated terms, measurand units, measurand sensing methods, sensor selection criteria, and a specification sheet. In addition, guidelines for selecting signal modifiers (amplifiers and filters) and signal processors (microcomputer and monitor) are also included.

9. It is found that almost all of the primary performance parameters of a hydraulic system (e.g., pressure, flow rate, etc.) can be measured by existing sensors. The capacity of some commercially

available microcomputers is sufficient to perform data manipulation and to control complex program sequences. However, in order to marry the sensors and microcomputer together to achieve the function of condition monitoring and process control, there are two disciplines which are severely insufficient in supporting such a marriage. They are the knowledge to assess system performance and a technique for microcomputer control.

10. Over the past two decades, the FPRC/OSU has spent a tremendous effort in the investigation of hydraulic component/system performance degradation and the study of the microcomputer control algorithm. The well-known component/system performance assessment theories developed and proved at the FPRC and recognized nationally and internationally are steps already overcome to the implementation of hydraulic systems with conditioning monitoring. Furthermore, from the success in using the distributed-intelligence microcomputer control algorithm in the development of the FPRC robot, it is concluded that the FPRC is ready to successfully develop the condition monitoring system. Consequently, it is highly recommended to extend this study to research on a condition monitoring system.

BIBLIOGRAPHY

1. Neubert, H.K.P., Instrument Transducers -- An Introduction to Their Performance and Design, 2nd Ed., Oxford Co., London, 1975.

2. Doebelin, E.O., Measurement Systems -- Application and Design, McGraw-Hill Book Co., New York, 1975.

3. Norton, H.N., Handbook of Transducers for Electronic Measuring Systems, Prentice-Hall Inc., Englewood Cliffs, N.J., 1969.

4. Liptak, B.G. and K. Venczel, Instrument Engineers' Handbook, Chilton Book Co., Radnor, PA, 1982.

5. Oliver, F. J., Practical Instrumentation Transducers, Hayden Book Co., New York, 1971.

END

FILMED

9-84

DTIC